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AN EXPERIMENTAL INVESTIGATION OF A SUBSCALE VARIABLE PRESSURE R--ETC(U)
FEB 77 D J HELTON, H G LUEDERS, J R ARVIN F33615-76-C-2068

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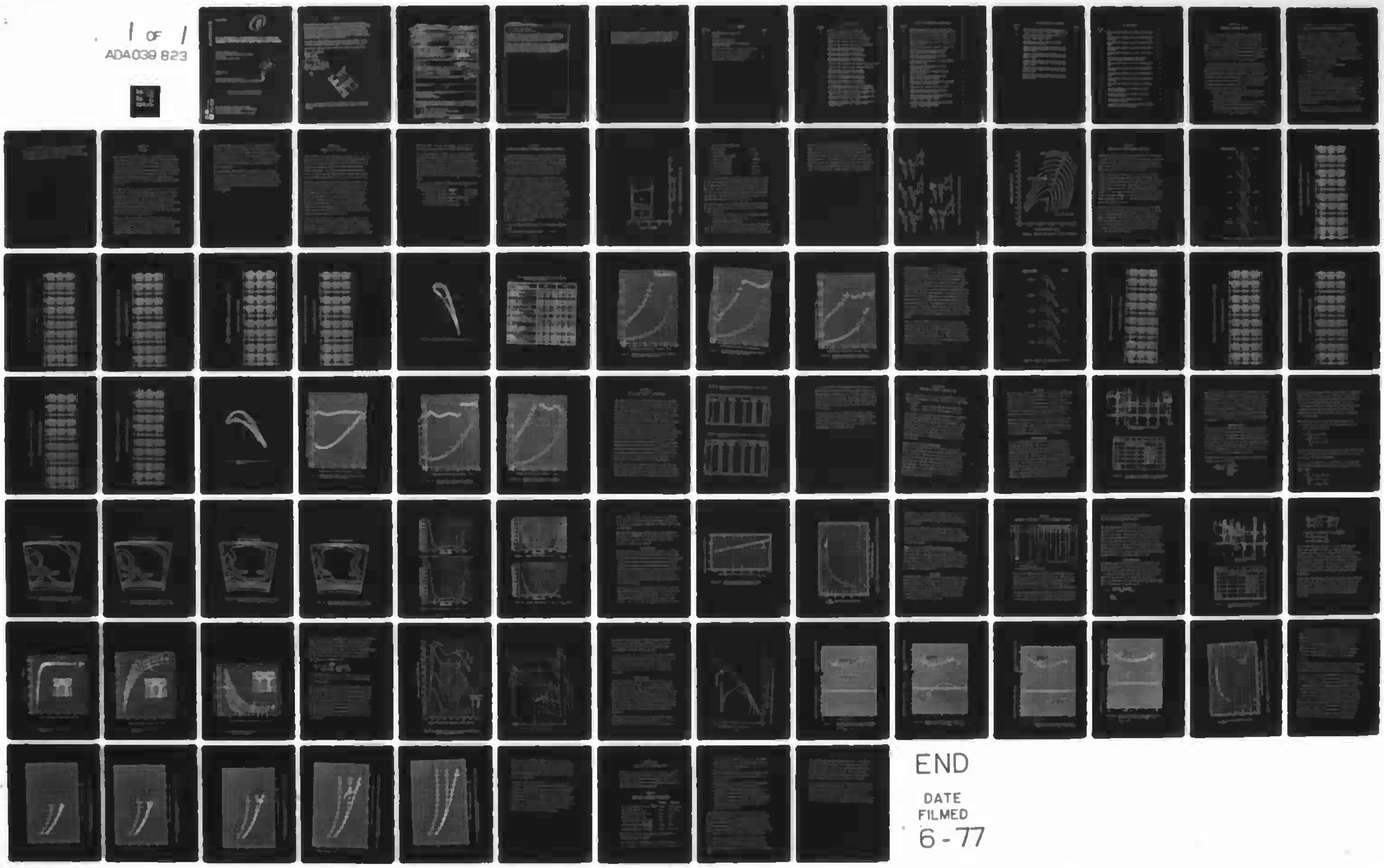

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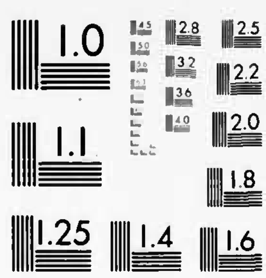

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AN EXPERIMENTAL INVESTIGATION OF A SUBSCALE VARIABLE PRESSURE RATIO HIGH THRU FLOW TURBINE

DETROIT DIESEL ALLISON
DIVISION OF GENERAL MOTORS CORPORATION
P.O. BOX 894
INDIANAPOLIS, INDIANA 46206

FEBRUARY 1977

TECHNICAL REPORT AFAPL-TR-77-7
FINAL REPORT FOR PERIOD JANUARY 1976 - DECEMBER 1976

AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Kervyn D Mach

KERVYN D. MACH
Project Engineer

FOR THE COMMANDER

James L. Radloff

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Chief, Components Branch

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This program investigates the aerodynamics of a subscale model of a variable pressure ratio high through flow turbine. The problem areas are:

- Small limit loading margin
- High rotor relative inlet Mach number
- Low aspect ratio blading

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- o Large rotor turning, and
- o Low hub/tip radius ratio.

The test program for the subscale HTF turbine was conducted in two phases. The initial test phase was a full annular stator cascade test designed to isolate the vane losses over a broad range of exit conditions. The overall vane passage losses closely matched the predicted design point value.

Phase II of the test program was the overall performance evaluation of the subscale HTF turbine. The turbine performance was investigated over a wide range of expansion ratios and equivalent speeds. Rotor exit surveys were conducted at selected operating conditions. The total/total efficiency of the turbine was experimentally determined to be 88.8 percent at design point conditions.

Perface

This final report was submitted by Detroit Diesel Allison, Division of General Motors Corporation, under Contract F33615-76-C-2068. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3066, Task 06 and Work Unit 28, with Wayne A. Tall, AFAPL/TBC, as Project Engineer. D. J. Helton of Detroit Diesel Allison was technically responsible for the work.

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SECTION I

INTRODUCTION AND OBJECTIVES

This program investigates the aerodynamic performance of a subscale model of a variable pressure ratio high through flow (HTF) turbine. This rig was sized relative to flow, speed, work and diameter such that a full size scale-up would drive and match an existing HTF compressor and combustor. This program was tailored to employ considerable hardware from a technology related IR&D effort currently underway in the area of high equivalent work gasifier turbines.

The HTF compressor concept was successfully demonstrated by Detroit Diesel Allison under USAF Contract F33615-72-C-1233 sponsored by the Aero Propulsion Laboratory. The high inlet Mach number combustor technology required for HTF engine development is currently in progress. This effort is funded by USAF Contract F33615-74-C-2028 and is also sponsored by the Aero Propulsion Laboratory. The goals of HTF turbine program Contract F33615-76-C-2068 are to:

- provide valuable detailed aero design information to augment the current technology base for the design of a HTF gas turbine engine
- demonstrate the aerodynamic performance of a subscale model of a full size HTF turbine which fully utilizes the technology advancements demonstrated in the companion combustor and compressor programs.

The goal efficiency was 87 percent for the subscale turbine rig based on a total-to-total expansion ratio.

The aero-designer is confronted with several major aerodynamic problems in the definition of a HTF turbine which employs (1) the increased rotational speeds, and (2) has a maximum diameter which is consistent with the reduced frontal area of the HTF compressor and combustor. Some of these problems have been addressed to individually and others are rational extensions of state-of-the-art. Never have all these problems been addressed in one design. The problem areas are:

- small limiting loading margin
- high rotor relative inlet Mach number
- low aspect ratio blading
- large rotor turning
- low hub/tip radius ratio.

These problem areas were investigated and evaluated in a three phase program consisting of the design, fabrication, and testing of an uncooled, fixed geometry subscale model of a single stage HTF turbine. The turbine for the subscale rig incorporated solid machined blading which was integral with the wheel. The blade, in the full size is suitable for air cooling and has satisfactory mechanical structural capability for high temperature engine application.

The results of the HTF turbine program will be used to bridge the technical gap required to apply some of the major payoffs

of the HTF compressor and combustion programs. These payoffs are reflected in an engine with fewer parts which reduces development time and cost. Tactical payoffs will be exhibited in reduced engine weight and frontal area.

SECTION II

SUMMARY

The Detroit Diesel Allison Division has designed, fabricated and successfully tested a subscale model of a variable pressure ratio, high through flow turbine. The single stage turbine rig was designed such that a full size scale-up is aerodynamically compatible with the existing 5-stage HTF compressor demonstrated by DDA and funded by USAF Contract F33615-72-C-1233. The full size turbine diameters are consistent with HMTC combustor program currently under development under USAF Contract F33615-74-C-2028.

The test program for the subscale HTF turbine was conducted in two phases. The initial test phase was a full annular stator cascade test designed to isolate the vane losses over a broad range of exit conditions. The overall vane passage losses closely matched the predicted design point value. The resulting contour maps showed possible performance improvements are potentially available in the near hub region. The vane exhibited excellent profile loss characteristics.

Phase II of the test program was the overall performance evaluation of the subscale HTF turbine. The turbine performance was investigated over a wide range of expansion ratios and equipment speeds. Rotor exit surveys were conducted at selected operating conditions. The total/total efficiency of the turbine

was experimentally determined to be slightly greater than 88.8 percent at design point conditions. This compares to a goal total/total efficiency of 87 percent for the subscale turbine. The measured flow capacity of the turbine was within 1.0 percent of the predicted design point value. The measured design point rotor hub reaction and turbine exit swirl were essentially the same as predicted.

This program has demonstrated the performance of a subscaled model of a HTF turbine designed to fully utilize the technology advancements of the HTF compressor and combustor programs. The resulting data provides valuable detailed aero-design information to augment the current design knowledge of the HTF gas turbine engine concepts.

SECTION III

DESIGN POINT SELECTION

Detroit Diesel Allison has conducted preliminary inter-discipline trade-off studies to define the turbine configurations suitable to drive the 5-stage HTF compressor. This study was primarily concerned with turbojet engines which employ variable flow capacity components. The variable geometry was employed to provide the engine with the capability of operating at a fixed compressor match point over a wide range of flight conditions.

One of the prime considerations in this study was defining the relationship between turbine blade stress level, turbine exit Mach number and turbine inlet total temperature (first rotor inlet temperature, RIT). The lower the selected cruise point RIT, the higher the turbine exit Mach number for a constant stress level (turbine exit area). For this study the turbine exit area was selected such that the maximum value of AeN^2 (untapered hub stress parameter) was 5.5×10^{10} in^2 rpm^2. The minimum cruise RIT was established by a turbine limiting loading constraint (maximum equivalent work level).

Turbine variable geometry permits the engine to operate at low values of RIT and thereby achieve good cruise SFC. By "opening" the turbine and operating at near stoichiometric inlet temperatures, a high thrust/weight ratio is also realized. The engine configuration resulting from this study employs a single stage, variable

geometry turbine which is air cooled. The minimum RIT for this engine was determined to be approximately 2200°F.

The turbine aerodynamic design point is usually chosen to correspond to that point requiring maximum performance and/or is the most demanding from an aerodynamic viewpoint. The aerodynamic design point for the HTF turbine subscale rig was selected to simulate a minimum RIT cruise condition. The operating point requires the turbine to have good performance while operating at or near maximum equivalent turbine work.

The equivalent aerodynamic design point conditions for the subscale HTF turbine rig were:

- equivalent flow rate, $\frac{(m\sqrt{\theta_{cr}}\varepsilon)_2}{\delta_1}$ 1.52 lbm/sec
- equivalent work level, $\Delta h/\theta_{cr2}$ 33.4 Btu/lbm
- equivalent rotational speed, $N/\sqrt{\theta_{cr2}}$ 25675 rpm
- goal total/total efficiency, η_{TT} 87%
- total/total expansion ratio, $R_{e_{TT}}$ 3.36

SECTION IV

SUBSCALE HTF TURBINE RIG FLOWPATH AND VELOCITY DIAGRAMS

The uncooled and fixed geometry subscale HTF turbine rig was designed to simulate the aerodynamic difficulties of the full size turbine operating at the design point. At this flight condition the full size turbine is operating at near limiting loading (maximum equivalent work) and the variable vane is in the "closed position" (minimum equivalent flow rate).

The flowpath of the subscale rig is a linear scale of the full size turbine. Figure 1 shows the subscale HTF turbine flowpath. Due to the high stress and temperature levels over which the full size turbine must operate, the use of a rotor tip shroud was not feasible. The rotor incorporates a constant tip diameter as a method of controlling tip clearance variations resulting in axial misalignments. The constant rotor hub geometry was employed in the full size turbine to reduce the "dead weight" at the wheel rim which in turn reduces wheel stress. This arrangement was found to result in a significant reduction in rotor assembly weight. The constant hub and tip diameters of the vane is consistent with the HTF turbine variable geometry requirement.

The salient flowpath characteristics of the subscale turbine rig are:

- o stator hub/tip diameter ratio 0.72

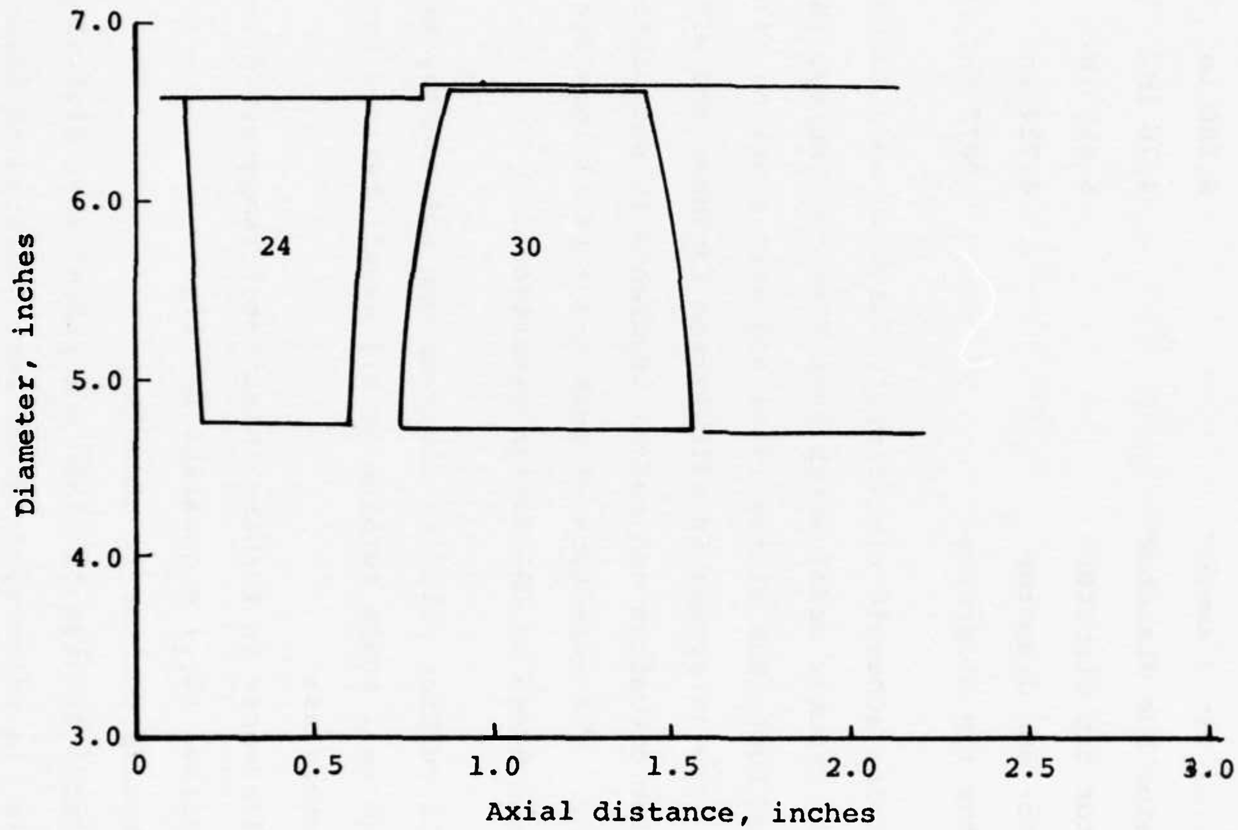


Figure 1 Subscale HTF turbine rig flowpath

o	rotor hub/tip diameter ratio	0.71
o	stator height	0.91 in.
o	rotor height	0.94 in.
o	overall turbine length	1.37 in.
o	stator tip diameter	6.586 in.
o	stator hub diameter	4.76 in.
o	rotor tip diameter	6.612 in.
o	rotor hub diameter	4.724 in.
o	rotor tip clearance	.0072 in.

The HTF turbine subscale rig velocity diagrams were calculated using a DDA computer model which satisfies continuity, energy and momentum equations at the inlet and exit stations of each blade row. The axisymmetric calculation includes the effects of streamline curvature and radial gradients in both enthalpy and enthropy. The selection of work and airfoil loss distributions were based on DDA design experience.

The subscale turbine velocity diagrams can not exactly match those of the full scale turbine at all axial stations because of such factors as:

- o differences in turbine inlet total temperature radial profile, (T_{T_1}) = constant for rig)
- o subscale turbine is uncooled
- o effects of size on blade row radial loss distributions.

The subscale rig velocity diagrams were designed to maintain rotor hub relative inlet Mach number and stage meanline reaction.

The vane and blade inlet and exit velocity triangles at 0 (hub), 25, 50 (mean), 75 and 100 (tip) percent locations are shown by Figure 2. These velocity diagrams simulate very closely the aerodynamic problem areas identified for the full size HTF turbine. The average values of stage load and flow coefficients for this condition were 2.10 and 0.69, respectively. Figure 3 shows the placement of the subscale rig on a conventional load coefficient - stage efficiency correlation chart.

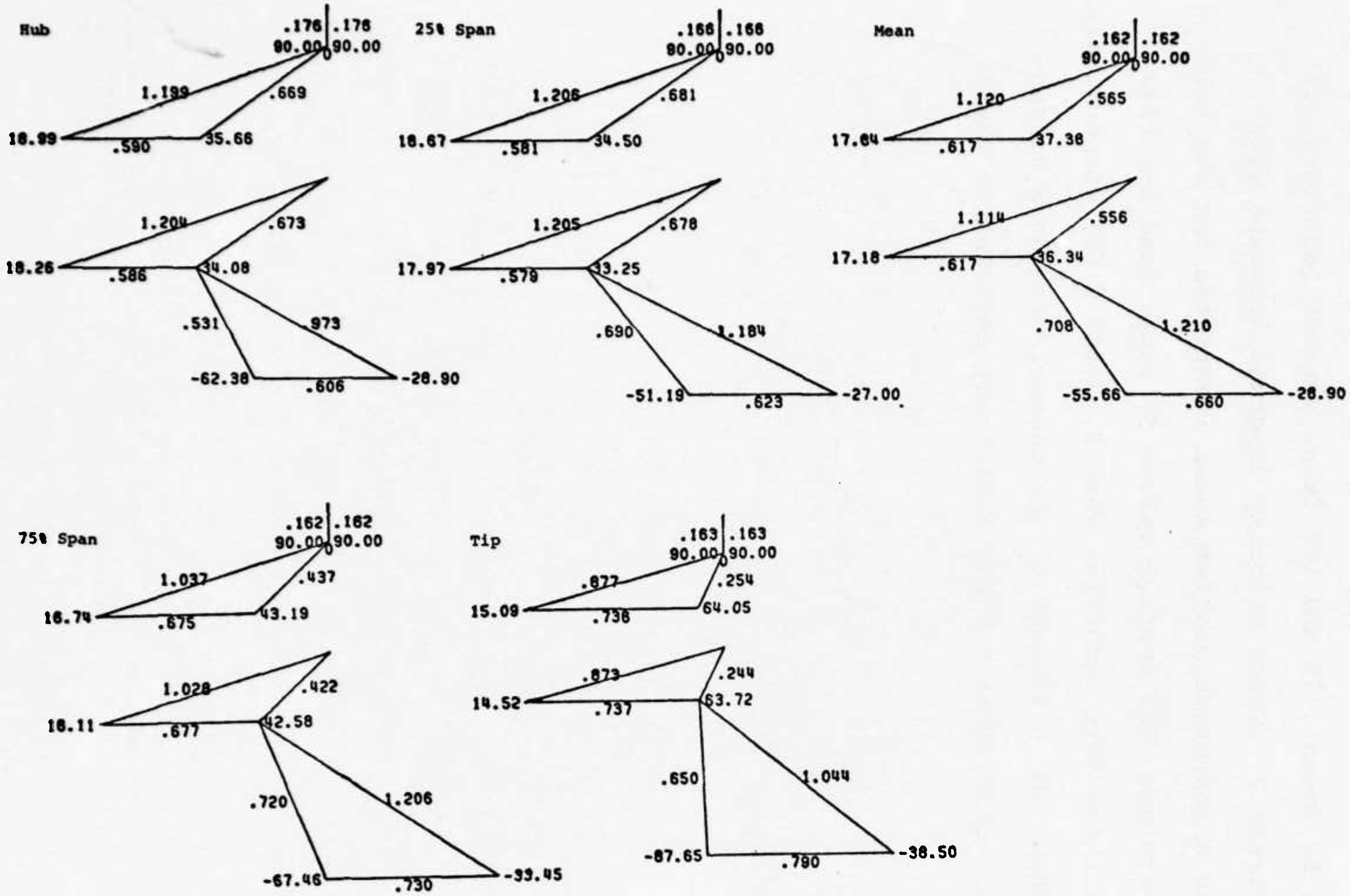


Figure 2 Subscale HTF turbine velocity diagrams

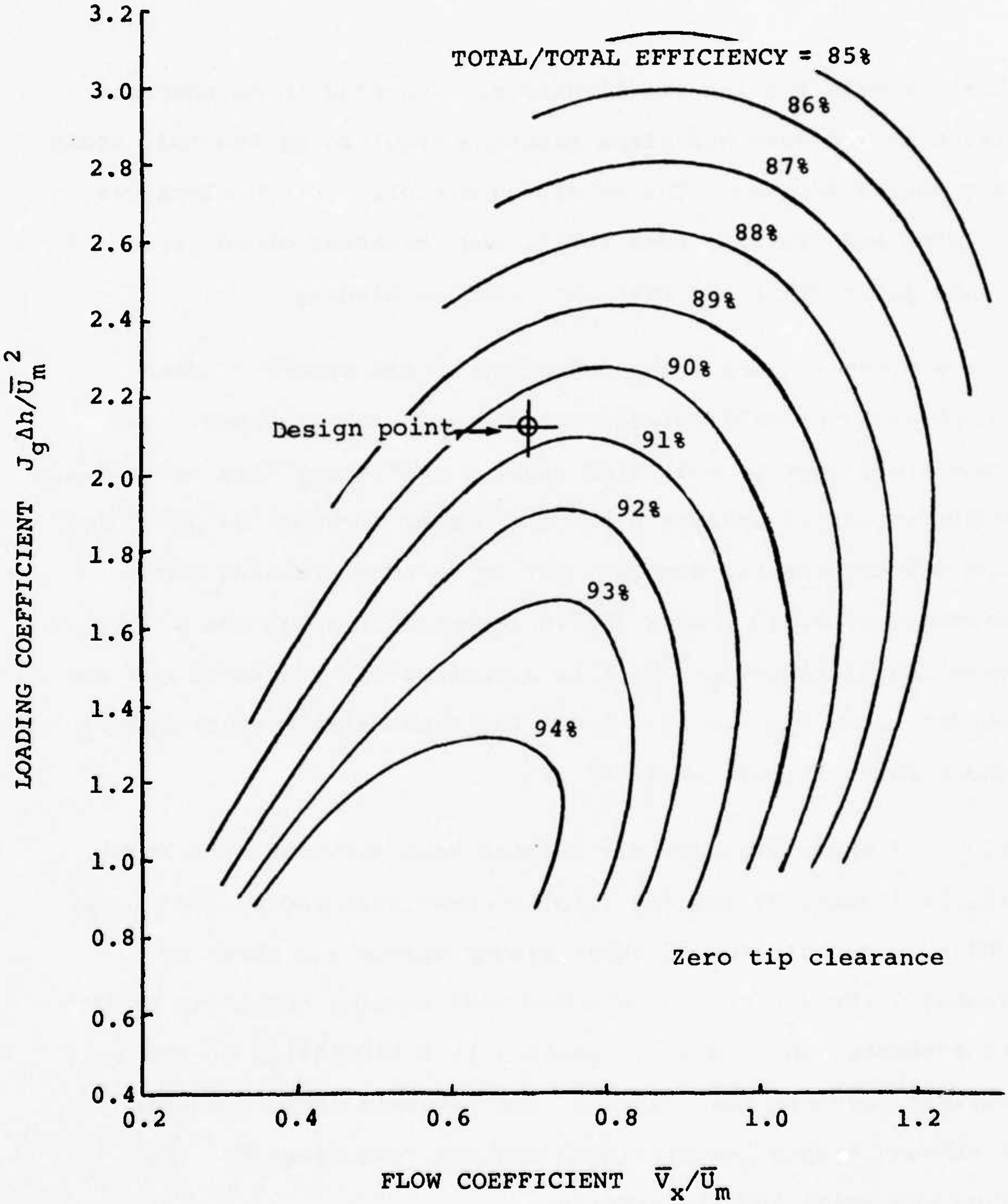


Figure 3 Subscale HTF turbine load chart placement

SECTION V

SUBSCALE HTF TURBINE BLADING DEFINITION

The subscale turbine rig blading was designed to be characteristic of the vane and blade sections required by the full scale air cooled turbine. The resulting airfoil section blockages, leading and trailing edge radii, and thickness/chord ratio are representative of the full size turbine blading.

For a given solidity, the selection of the number of vanes involved a tradeoff between aspect ratio and blockage. The vane cross section must also provide sufficient area for radial distribution of cooling air. The number of vanes selected for the HTF turbine rig was 24. For an assumed trailing edge diameter of 0.016 inches (0.070 inches full size) the resultant meanline blockage ($\frac{Dte}{0 + Dte}$) is approximately 7 percent and the aspect ratio ($\frac{h}{C_T}$) is near 1.0. The vane maximum thickness to chord ratio (T_m/C_T) is 0.183.

Figure 4 shows the subscale turbine vane sections at 0 (hub), 25, 50 (lean), 75 and 100 (tip) percent span radial locations. The x, y coordinates of these planar slices are shown by Tables 1 through 5. The stacked vane section composite plot is presented in Figure 5. Table 6 is a tabulation of the salient physical parameters of the subscale vane. Figures 6 through 8 show the predicted surface velocities for the vane hub, mean and tip sections.

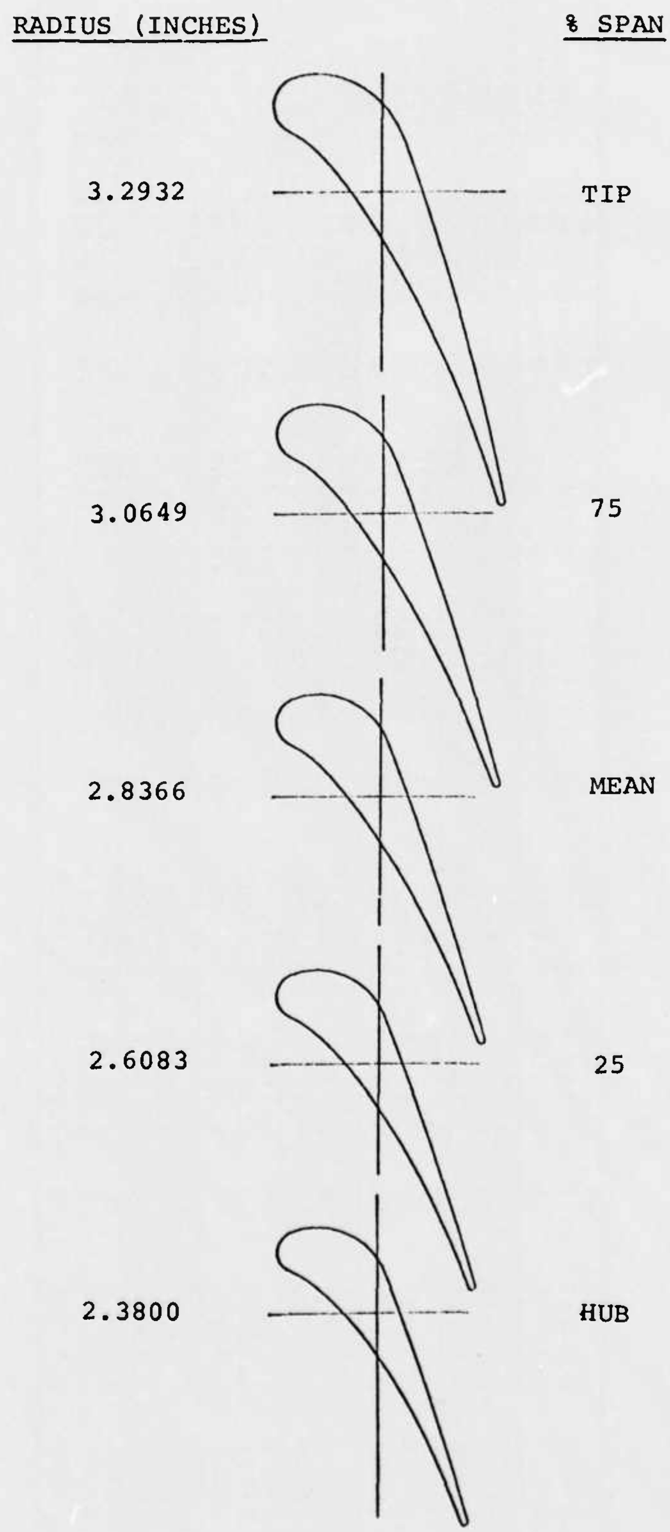


Figure 4 Subscale HTF turbine vane planar slices

Table 1 Subscale HTF turbine rig stator coordinates - hub

Planar Slice Radius = 2.3800 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.19670	0.18289	2	-0.16897	0.19202	3	-0.13880	0.19583	4	-0.10847	0.19376
5	-0.07910	0.18596	6	-0.05171	0.17280	7	-0.02724	0.15480	8	-0.00648	0.13264
9	0.00993	0.10711	10	0.02172	0.07912	11	0.03213	0.05058	12	0.04241	0.02198
13	0.05256	-0.00667	14	0.06259	-0.03536	15	0.07249	-0.06411	16	0.08228	-0.09292
17	0.09196	-0.12177	18	0.10153	-0.15069	19	0.11100	-0.17966	20	0.12036	-0.20869
21	0.12963	-0.23778	22	0.13881	-0.26693	23	0.14790	-0.29615	24	0.15690	-0.32543
25	0.16583	-0.35478	26	0.17468	-0.38419	27	0.18345	-0.41368	28	0.19215	-0.44324
29	0.20082	-0.47295	30	0.20113	-0.47513	31	0.20083	-0.47732	32	0.19994	-0.47934
33	0.19852	-0.48104	34	0.19670	-0.48228	35	0.19460	-0.48297	36	0.19239	-0.48305
37	0.19025	-0.48252	38	0.18833	-0.48142	39	0.18679	-0.47984	40	0.18575	-0.47789
41	0.17676	-0.45373	42	0.16766	-0.42993	43	0.15834	-0.40625	44	0.14880	-0.38270
45	0.13901	-0.35929	46	0.12897	-0.33601	47	0.11866	-0.31289	48	0.10806	-0.28993
49	0.09717	-0.26713	50	0.08595	-0.24452	51	0.07441	-0.22210	52	0.06251	-0.19989
53	0.05025	-0.17790	54	0.03760	-0.15614	55	0.02455	-0.13465	56	0.01107	-0.11344
57	-0.00285	-0.09253	58	-0.01725	-0.07195	59	-0.03214	-0.05175	60	-0.04757	-0.03195
61	-0.06357	-0.01262	62	-0.08020	0.00617	63	-0.09751	0.02433	64	-0.11559	0.04173
65	-0.13452	0.05819	66	-0.15444	0.07346	67	-0.17548	0.08714	68	-0.19758	0.09860
69	-0.20593	0.10348	70	-0.21307	0.11000	71	-0.21870	0.11786	72	-0.22255	0.12672
73	-0.22447	0.13620	74	-0.22437	0.14587	75	-0.22226	0.15530	76	-0.21821	0.16408
77	-0.21243	0.17183	78	-0.20515	0.17819						

Table 2 Subscale HTF turbine rig stator coordinates - 25% span

Planar Slice Radius = 2.6083 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.19834	0.20064	2	-0.16908	0.21001	3	-0.13711	0.21336	4	-0.10515	0.21006
5	-0.07455	0.20035	6	-0.04652	0.18472	7	-0.02216	0.16387	8	-0.00233	0.13869
9	0.01228	0.11017	10	0.02371	0.08018	11	0.03497	0.05014	12	0.04611	0.02005
13	0.05712	-0.01008	14	0.06802	-0.04027	15	0.07880	-0.07051	16	0.08947	-0.10082
17	0.10003	-0.13120	18	0.11048	-0.16166	19	0.12083	-0.19219	20	0.13107	-0.22281
21	0.14122	-0.25352	22	0.15127	-0.28433	23	0.16122	-0.31524	24	0.17108	-0.34625
25	0.18085	-0.37738	26	0.19054	-0.40863	27	0.20014	-0.44001	28	0.20966	-0.47152
29	0.21913	-0.50327	30	0.21946	-0.50546	31	0.21917	-0.50765	32	0.21829	-0.50968
33	0.21688	-0.51138	34	0.21506	-0.51264	35	0.21296	-0.51334	36	0.21075	-0.51343
37	0.20860	-0.51292	38	0.20667	-0.51182	39	0.20512	-0.51024	40	0.20407	-0.50830
41	0.19435	-0.48260	42	0.18444	-0.45722	43	0.17427	-0.43203	44	0.16385	-0.40701
45	0.15316	-0.38217	46	0.14220	-0.35751	47	0.13094	-0.33305	48	0.11939	-0.30878
49	0.10754	-0.28472	50	0.09538	-0.26085	51	0.08290	-0.23720	52	0.07009	-0.21376
53	0.05695	-0.19055	54	0.04347	-0.16756	55	0.02964	-0.14482	56	0.01544	-0.12233
57	0.00086	-0.10011	58	-0.01412	-0.07818	59	-0.02953	-0.05655	60	-0.04540	-0.03528
61	-0.06179	-0.01440	62	-0.07874	0.00601	63	-0.09635	0.02586	64	-0.11473	0.04501
65	-0.13402	0.06324	66	-0.15443	0.08022	67	-0.17620	0.09543	68	-0.19951	0.10795
69	-0.20868	0.11333	70	-0.21652	0.12051	71	-0.22269	0.12917	72	-0.22691	0.13893
73	-0.22900	0.14936	74	-0.22887	0.15999	75	-0.22652	0.17036	76	-0.22205	0.18001
77	-0.21566	0.18851	78	-0.20764	0.19549						

Table 3 Subscale HTF turbine rig stator coordinates - mean

Planar Slice Radius = 2.8366 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.20000	0.21842	2	-0.16877	0.22825	3	-0.13449	0.23136	4	-0.10033	0.22705
5	-0.06787	0.21564	6	-0.03849	0.19774	7	-0.01343	0.17421	8	0.00633	0.14612
9	0.02023	0.11471	10	0.03220	0.08249	11	0.04405	0.05019	12	0.05577	0.01784
13	0.06736	-0.01456	14	0.07884	-0.04702	15	0.09021	-0.07958	16	0.10146	-0.11223
17	0.11261	-0.14498	18	0.12365	-0.17784	19	0.13459	-0.21081	20	0.14542	-0.24390
21	0.15615	-0.27713	22	0.16678	-0.31051	23	0.17730	-0.34404	24	0.18772	-0.37773
25	0.19804	-0.41160	26	0.20824	-0.44566	27	0.21834	-0.47992	28	0.22832	-0.51439
29	0.23822	-0.54920	30	0.23852	-0.55140	31	0.23820	-0.55360	32	0.23729	-0.55562
33	0.23586	-0.55731	34	0.23402	-0.55854	35	0.23191	-0.55922	36	0.22969	-0.55929
37	0.22754	-0.55875	38	0.22563	-0.55763	39	0.22409	-0.55603	40	0.22305	-0.55407
41	0.21274	-0.52598	42	0.20218	-0.49823	43	0.19133	-0.47073	44	0.18019	-0.44348
45	0.16873	-0.41648	46	0.15696	-0.38973	47	0.14486	-0.36324	48	0.13244	-0.33700
49	0.11969	-0.31101	50	0.10660	-0.28527	51	0.09320	-0.25978	52	0.07946	-0.23454
53	0.06541	-0.20955	54	0.05104	-0.18479	55	0.03635	-0.16028	56	0.02134	-0.13601
57	0.00601	-0.11199	58	-0.00966	-0.08823	59	-0.02568	-0.06474	60	-0.04211	-0.04156
61	-0.05899	-0.01871	62	-0.07640	0.00372	63	-0.09443	0.02564	64	-0.11324	0.04690
65	-0.13303	0.06727	66	-0.15406	0.08633	67	-0.17673	0.10342	68	-0.20152	0.11728
69	-0.21150	0.12319	70	-0.22003	0.13105	71	-0.22673	0.14052	72	-0.23130	0.15117
73	-0.23355	0.16255	74	-0.23338	0.17414	75	-0.23079	0.18545	76	-0.22589	0.19596
77	-0.21891	0.20522	78	-0.21015	0.21282						

Table 4 Subscale HTF turbine rig stator coordinates - 75% span

Planar Slice Radius = 3.0649 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.20101	0.23645	2	-0.16791	0.24605	3	-0.13084	0.24760	4	-0.09438	0.24060
5	-0.06027	0.22593	6	-0.02985	0.20462	7	-0.00414	0.17785	8	0.01616	0.14679
9	0.03082	0.11269	10	0.04371	0.07787	11	0.05642	0.04297	12	0.06897	0.00799
13	0.08136	-0.02708	14	0.09358	-0.06225	15	0.10564	-0.09753	16	0.11754	-0.13293
17	0.12928	-0.16846	18	0.14087	-0.20414	19	0.15230	-0.23997	20	0.16357	-0.27596
21	0.17468	-0.31214	22	0.18563	-0.34851	23	0.19641	-0.38508	24	0.20703	-0.42187
25	0.21747	-0.45890	26	0.22774	-0.49617	27	0.23784	-0.53402	28	0.24774	-0.57245
29	0.25745	-0.61145	30	0.25767	-0.61364	31	0.25729	-0.61582	32	0.25632	-0.61780
33	0.25484	-0.61944	34	0.25297	-0.62062	35	0.25085	-0.62124	36	0.24864	-0.62125
37	0.24652	-0.62066	38	0.24463	-0.61951	39	0.24314	-0.61788	40	0.24214	-0.61591
41	0.23128	-0.58449	42	0.22011	-0.55346	43	0.20863	-0.52277	44	0.19686	-0.49274
45	0.18478	-0.46307	46	0.17238	-0.43367	47	0.15967	-0.40454	48	0.14664	-0.37568
49	0.13329	-0.34708	50	0.11962	-0.31875	51	0.10563	-0.29068	52	0.09132	-0.26287
53	0.07670	-0.23530	54	0.06177	-0.20799	55	0.04652	-0.18092	56	0.03094	-0.15411
57	0.01503	-0.12756	58	-0.00125	-0.10127	59	-0.01791	-0.07528	60	-0.03501	-0.04961
61	-0.05260	-0.02430	62	-0.07078	0.00056	63	-0.08965	0.02488	64	-0.10939	0.04848
65	-0.13024	0.07111	66	-0.15251	0.09232	67	-0.17669	0.11131	68	-0.20341	0.12658
69	-0.21427	0.13303	70	-0.22353	0.14162	71	-0.23079	0.15195	72	-0.23571	0.16358
73	-0.23809	0.17598	74	-0.23781	0.18861	75	-0.23490	0.20089	76	-0.22947	0.21230
77	-0.22177	0.22230	78	-0.21214	0.23048						

Table 5 Subscale HTF turbine rig stator coordinates - tip

Planar Slice Radius = 3.2932 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.20199	0.25441	2	-0.16578	0.26418	3	-0.12473	0.26453	4	-0.08474	0.25535
5	-0.04761	0.23798	6	-0.01460	0.21376	7	0.01345	0.18399	8	0.03601	0.14989
9	0.05276	0.11262	10	0.06615	0.07396	11	0.07930	0.03523	12	0.09224	-0.00361
13	0.10495	-0.04256	14	0.11745	-0.08164	15	0.12973	-0.12088	16	0.14178	-0.16029
17	0.15362	-0.19989	18	0.16522	-0.23971	19	0.17660	-0.27975	20	0.18774	-0.32005
21	0.19864	-0.36062	22	0.20928	-0.40149	23	0.21967	-0.44268	24	0.22979	-0.48421
25	0.23963	-0.52611	26	0.24918	-0.56840	27	0.25842	-0.61110	28	0.26735	-0.65425
29	0.27596	-0.69793	30	0.27607	-0.70013	31	0.27558	-0.70227	32	0.27453	-0.70419
33	0.27299	-0.70576	34	0.27108	-0.70685	35	0.26895	-0.70737	36	0.26675	-0.70730
37	0.26466	-0.70663	38	0.26283	-0.70541	39	0.26141	-0.70374	40	0.26049	-0.70175
41	0.24968	-0.66674	42	0.23850	-0.63194	43	0.22698	-0.59751	44	0.21510	-0.56346
45	0.20286	-0.52977	46	0.19026	-0.49644	47	0.17728	-0.46346	48	0.16393	-0.43082
49	0.15020	-0.39852	50	0.13610	-0.36655	51	0.12162	-0.33491	52	0.10678	-0.30358
53	0.09158	-0.27255	54	0.07601	-0.24183	55	0.06008	-0.21140	56	0.04379	-0.18127
57	0.02712	-0.15143	58	0.01005	-0.12188	59	-0.00745	-0.09265	60	-0.02542	-0.06377
61	-0.04393	-0.03526	62	-0.06307	-0.00721	63	-0.08300	0.02027	64	-0.10389	0.04702
65	-0.12603	0.07275	66	-0.14984	0.09694	67	-0.17596	0.11865	68	-0.20536	0.13595
69	-0.21710	0.14293	70	-0.22710	0.15223	71	-0.23491	0.16343	72	-0.24019	0.17603
73	-0.24269	0.18946	74	-0.24230	0.20311	75	-0.23904	0.21637	76	-0.23306	0.22865
77	-0.22462	0.23939	78	-0.21411	0.24810						

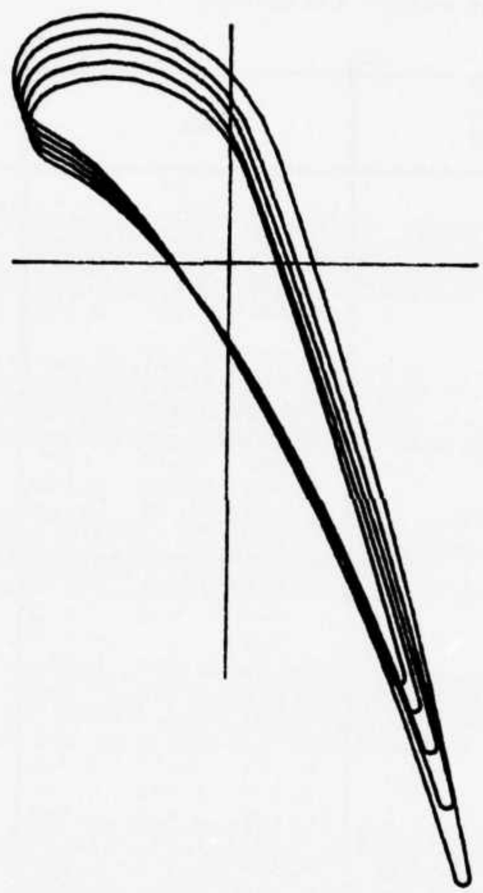


Figure 5 Subscale HTF turbine vane section composite

Table 6 Tabulation of the subscale HTF turbine vane and blade geometric parameters

CONICAL SECTION PARAMETERS	VANE			BLADE		
NUMBER OF AIRFOILS		24			30	
INLET RADIUS	10.425	12.442	14.425	10.345	12.192	14.480
INLET METAL ANGLE	90.0	90.0	90.0	38.9	40.5	58.7
INCIDENCE	0.0	0.0	0.0	5.0	5.0	-5.0
DELTA BETA1	24.0	24.0	24.0	16.0	17.8	24.0
LEADING EDGE RADIUS	0.200	0.240	0.280	0.100	0.100	0.100
THROAT RADIUS	10.425	12.425	14.425	10.345	12.412	14.480
THROAT	0.762	0.942	0.937	0.960	1.179	1.444
PCX MAX. CURV.	0.500	0.500	0.500	0.400	0.500	0.990
PC MAX. CURV.	******	******	******	0.700	0.500	0.010
SUCTION SURF. MAX. CURV.	1.48	1.46	1.71	1.05	1.24	1.53
PERPQ	0.600	0.400	0.400	0.500	0.600	0.400
PRESSURE SURF. MAX. CURV.	1.16	1.68	1.81	0.79	1.05	2.01
EXIT RADIUS	10.425	12.419	14.425	10.345	12.461	14.480
MERIDIONAL CHORD	1.850	2.051	2.250	3.550	3.203	2.400
DELTA BETA2	4.0	4.0	6.0	4.0	3.0	4.0
DOWN STREAM TURNING	5.0	5.0	8.0	8.0	6.0	8.0
TRAILING EDGE RADIUS	0.035	0.035	0.035	0.037	0.037	0.037
CONE ANGLE	0.0	-0.6	0.0	0.0	4.9	0.0
TRAILING EDGE CURV. SLOPE	0.0	0.0	0.0	0.0	0.0	0.0
SPACING	2.729	3.253	3.776	2.167	2.600	3.033
TRUE CHORD	3.369	3.853	4.596	4.059	3.912	3.288
SOLIDITY CM/S	0.678	0.630	0.596	1.638	1.232	0.791
SOLIDITY CT/S	1.235	1.185	1.217	1.873	1.505	1.084
X MAX. THICKNESS/CM	0.353	0.329	0.347	0.344	0.326	0.313
MAX. THICKNESS	0.626	0.704	0.781	0.839	0.735	0.571
X THROAT/CM	0.577	0.537	0.577	0.753	0.667	0.473
MAX. THICKNESS/CT	0.186	0.183	0.170	0.207	0.188	0.174
AREA	1.140	1.448	2.007	2.148	1.704	1.094
RLE/CT	0.059	0.062	0.061	0.025	0.026	0.030
BLOCKAGE	0.092	0.074	0.075	0.078	0.064	0.052
THROAT/SPACING	0.279	0.290	0.248	0.443	0.454	0.476
COMPRESSIBLE ZWEIFEL	0.475	0.611	0.555	0.548	0.657	0.563
INCOMPRESSIBLE ZWEIFEL	0.915	0.920	0.840	0.927	1.205	1.446

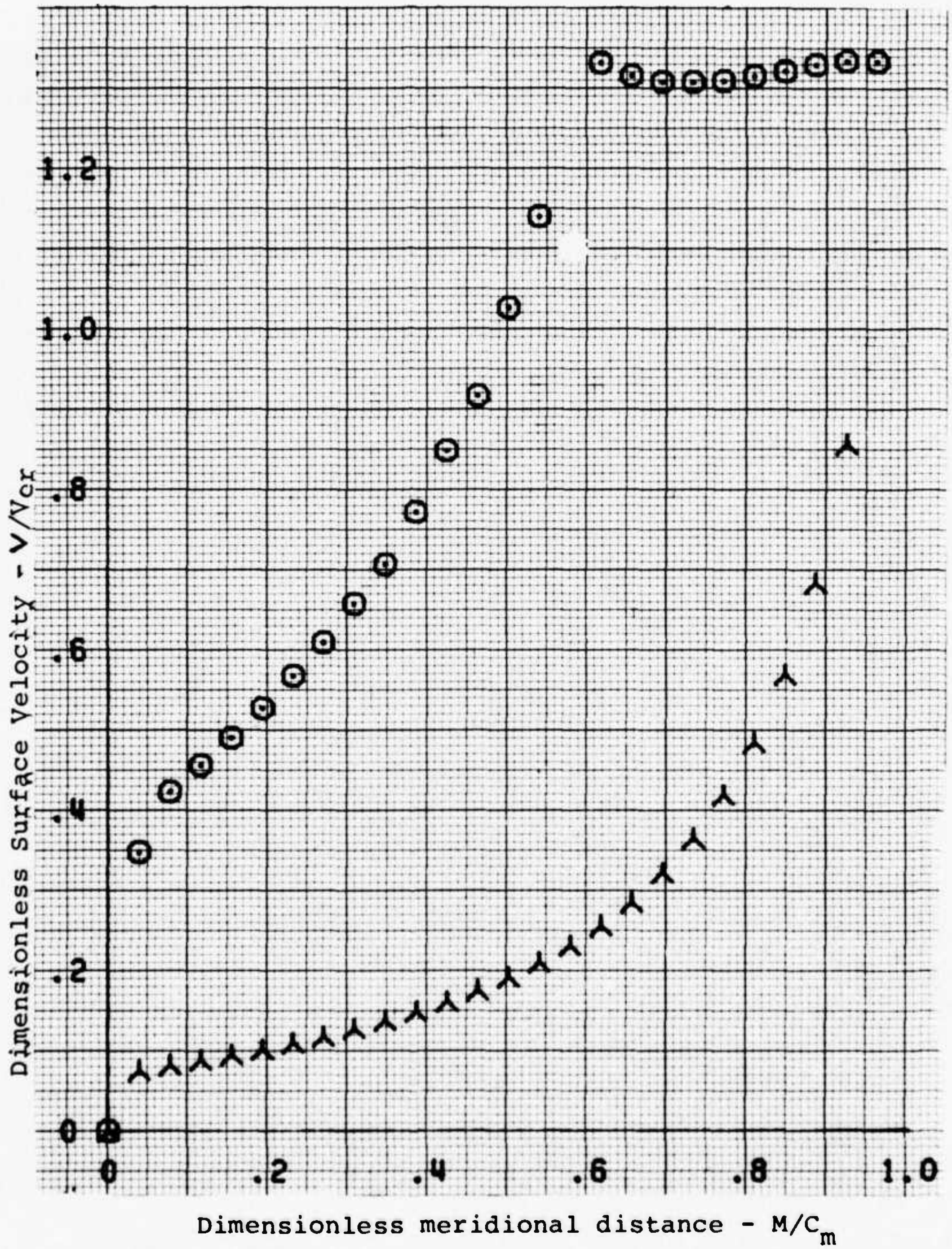


Figure 6 Subscale HTF turbine vane surface velocity distribution - hub section

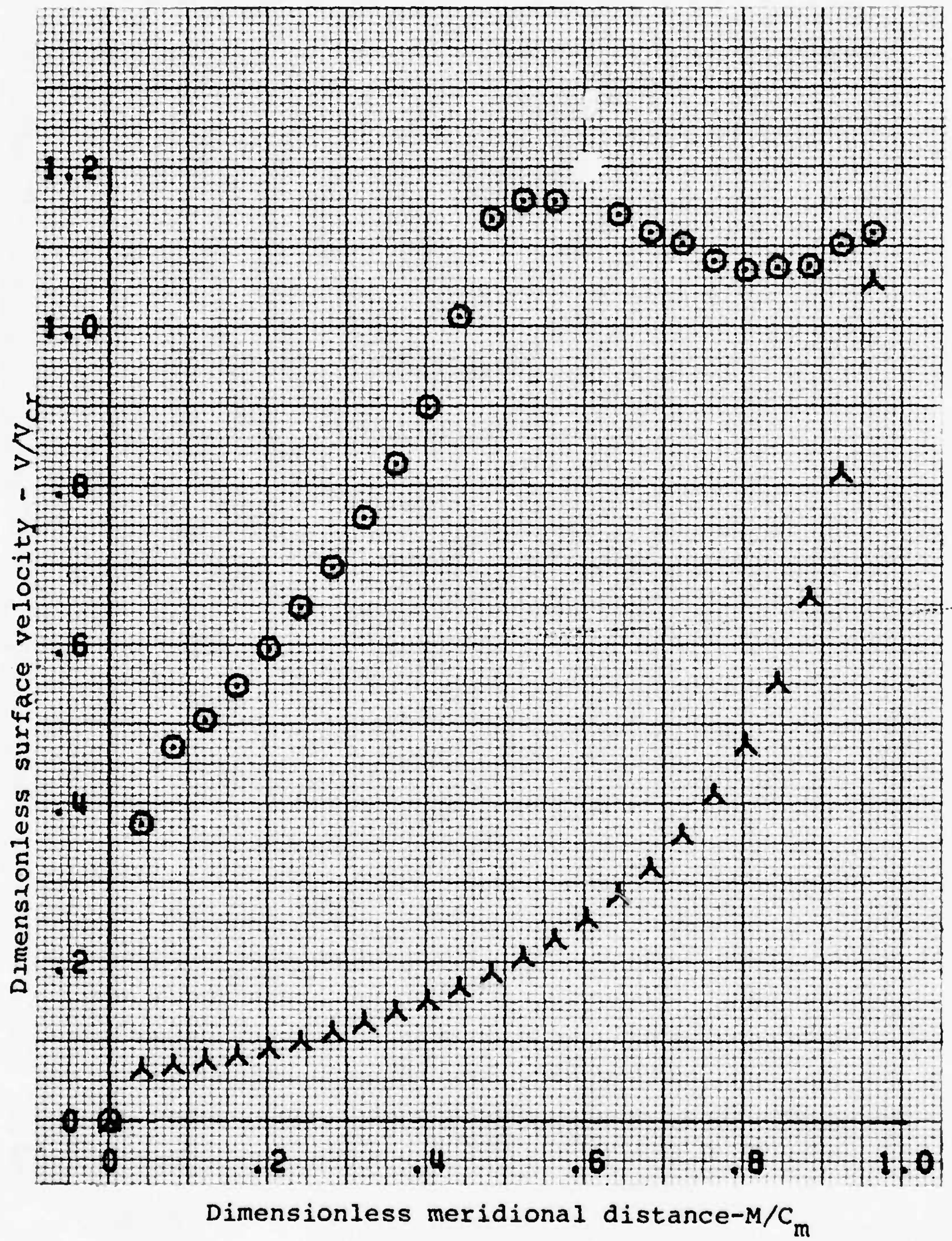


Figure 7 Subscale HTF turbine vane surface velocity distribution - mean section

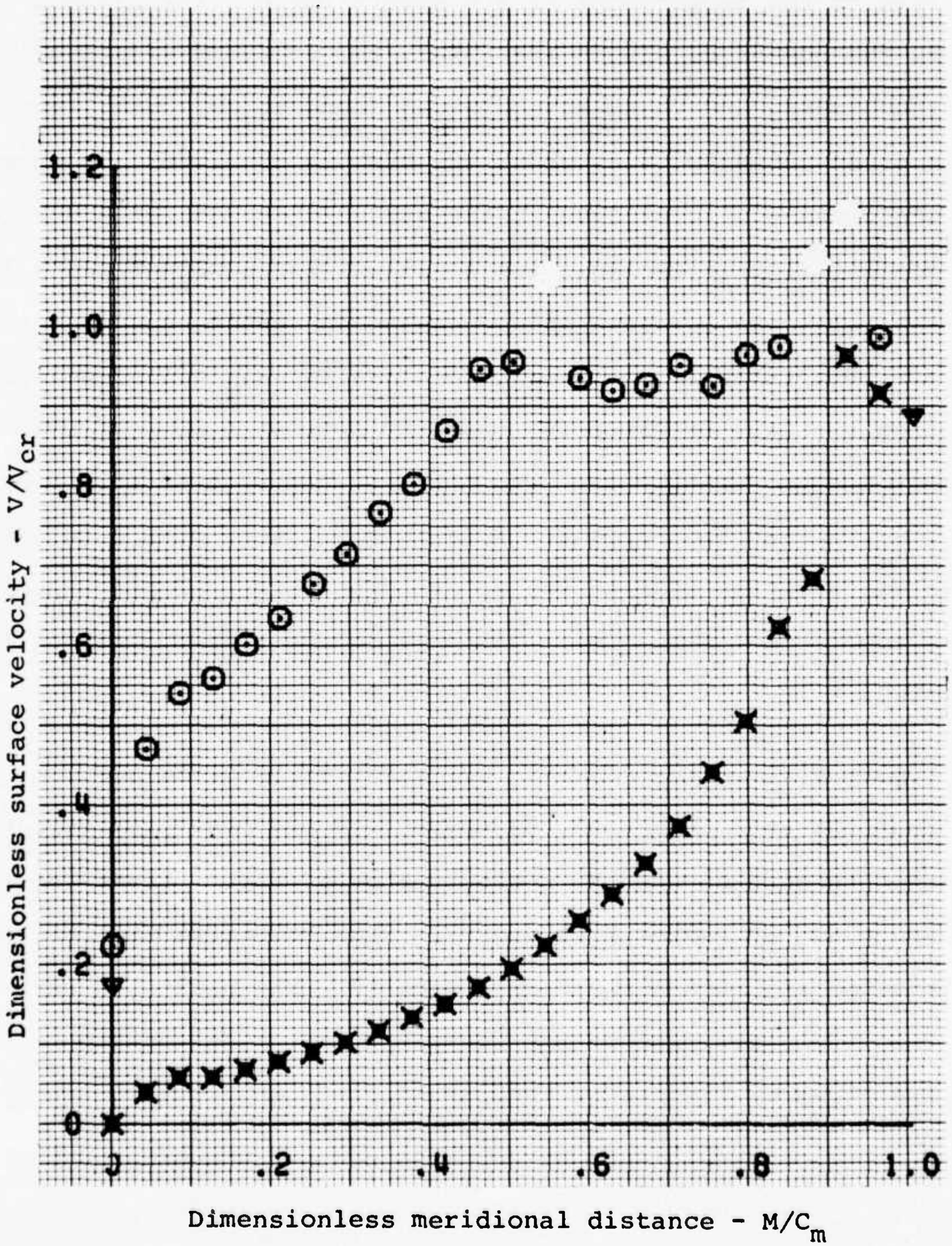


Figure 8 Subscale HTF turbine vane surface velocity distribution - tip section

The combined considerations of heat transfer and structures lead to the requirement of low aspect ratio rotor blades. As the number of blades increases, the combined weight of the blading and wheel assembly was found to decrease. For a given solidity, increasing the numbers of airfoils reduces the cross sectional area at the hub section available for coolant flow injection. Due to structural considerations for the full size turbine, this decrease in cooling air feed cross sectional area is not proportional to the airfoil cross sectional area. It was found that the optimum number of blades to be approximately 30. The meanline blockage of this blade row is about 6.0 percent. This is consistent with a full size blade trailing edge thickness of .075 inches. Table 6 presents a tabulation of the important physical characteristics of this blade.

Figure 9 shows the subscale HTF turbine rig blade section profiles at 0 (hub), 25, 50 (mean), 75 and 100 (tip) percent span locations. The x, y coordinates of these planar sections are shown by Tables 7 through 11. The composite plot of the stacked sections is shown by Figure 10. The predicted surface velocity distributions for the rotor hub, mean and tip sections are shown by Figures 11 through 13.

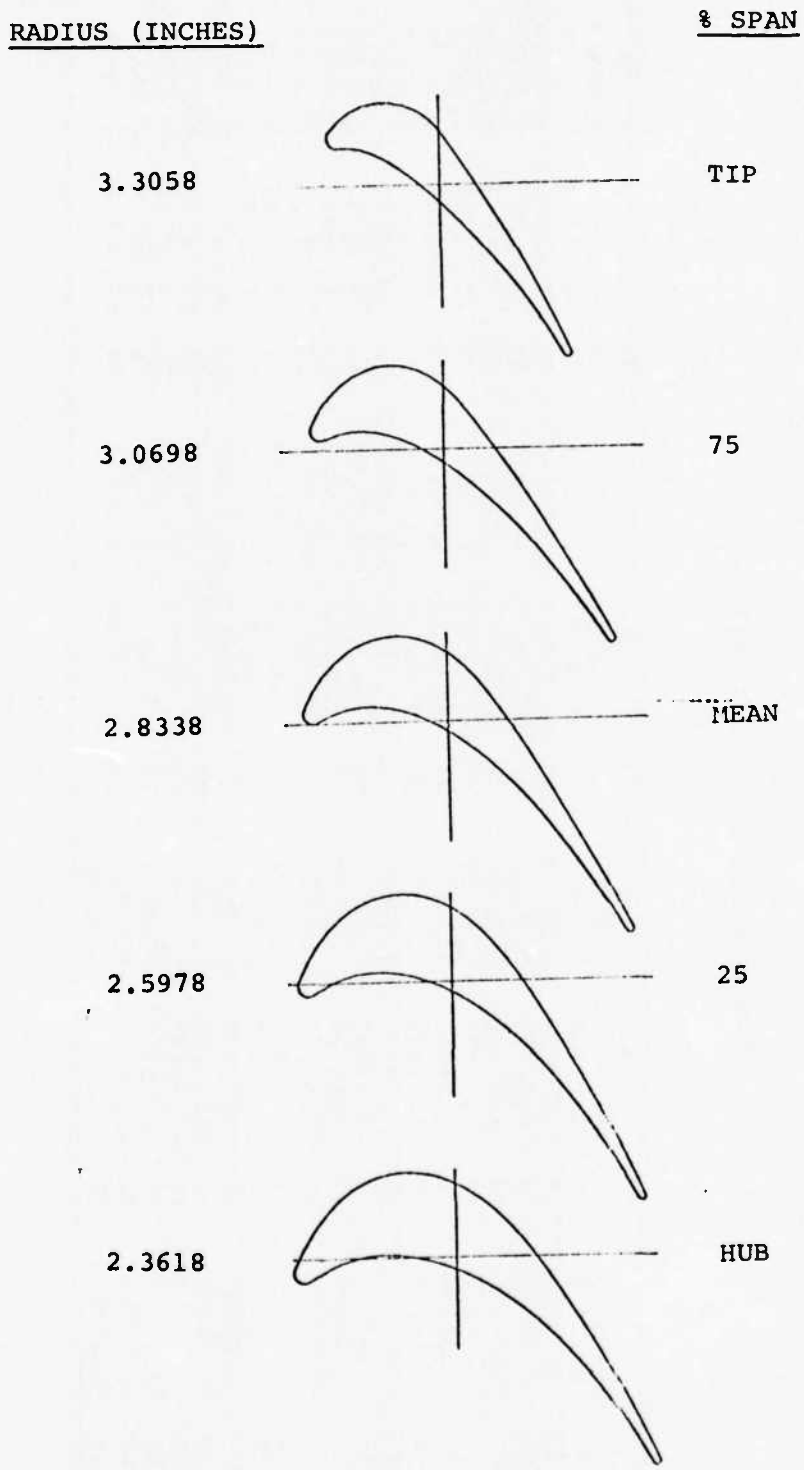


Figure 9 Subscale HTF turbine blade planar slices

Table 7 Subscale HTF turbine rig rotor coordinates - hub

Planar Slice Radius = 2.3618 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.36126	-0.02267	2	-0.34259	0.01779	3	-0.32066	0.05695	4	-0.29480	0.09367
5	-0.26444	0.12678	6	-0.22938	0.15481	7	-0.18996	0.17620	8	-0.14719	0.18951
9	-0.10267	0.19380	10	-0.05826	0.18893	11	-0.01563	0.17569	12	0.02418	0.15548
13	0.06076	0.12986	14	0.09424	0.10024	15	0.12503	0.06776	16	0.15363	0.03329
17	0.18055	-0.00254	18	0.20626	-0.03930	19	0.23107	-0.07667	20	0.25516	-0.11450
21	0.27860	-0.15270	22	0.30139	-0.19125	23	0.32352	-0.23010	24	0.34500	-0.26922
25	0.36583	-0.30858	26	0.38602	-0.34814	27	0.40557	-0.38786	28	0.42450	-0.42771
29	0.44271	-0.46741	30	0.44338	-0.46971	31	0.44339	-0.47210	32	0.44275	-0.47441
33	0.44149	-0.47644	34	0.43972	-0.47805	35	0.43757	-0.47911	36	0.43521	-0.47954
37	0.43283	-0.47930	38	0.43061	-0.47841	39	0.42872	-0.47695	40	0.42730	-0.47502
41	0.41092	-0.44523	42	0.39379	-0.41551	43	0.37597	-0.38609	44	0.35742	-0.35702
45	0.33811	-0.32835	46	0.31799	-0.30016	47	0.29705	-0.27251	48	0.27523	-0.24546
49	0.25253	-0.21910	50	0.22890	-0.19352	51	0.20433	-0.16879	52	0.17879	-0.14503
53	0.15228	-0.12232	54	0.12478	-0.10081	55	0.09629	-0.08062	56	0.06679	-0.06192
57	0.03629	-0.04489	58	0.00481	-0.02976	59	-0.02763	-0.01680	60	-0.06095	-0.00635
61	-0.09503	0.00123	62	-0.12969	0.00551	63	-0.16459	0.00609	64	-0.19934	0.00267
65	-0.23341	-0.00490	66	-0.26633	-0.01652	67	-0.29767	-0.03186	68	-0.32712	-0.05042
69	-0.33185	-0.05295	70	-0.33703	-0.05431	71	-0.34239	-0.05443	72	-0.34764	-0.05330
73	-0.35247	-0.05098	74	-0.35663	-0.04760	75	-0.35989	-0.04334	76	-0.36207	-0.03844
77	-0.36305	-0.03317	78	-0.36277	-0.02782						

Table 8 Subscale HTF turbine rig rotor coordinates - 25% span

Planar Slice Radius = 2.5978 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.34260	0.00304	2	-0.32499	0.04263	3	-0.30316	0.08079	4	-0.27677	0.11597
5	-0.24550	0.14688	6	-0.20946	0.17196	7	-0.16935	0.18962	8	-0.12654	0.19849
9	-0.08291	0.19780	10	-0.04054	0.18766	11	-0.00103	0.16931	12	0.03486	0.14455
13	0.06717	0.11516	14	0.09641	0.08261	15	0.12327	0.04795	16	0.14842	0.01193
17	0.17245	-0.02493	18	0.19576	-0.06233	19	0.21853	-0.10010	20	0.24082	-0.13822
21	0.26262	-0.17665	22	0.28390	-0.21538	23	0.30467	-0.25440	24	0.32492	-0.29368
25	0.34465	-0.33320	26	0.36384	-0.37295	27	0.38252	-0.41290	28	0.40066	-0.45303
29	0.41820	-0.49314	30	0.41883	-0.49547	31	0.41880	-0.49788	32	0.41810	-0.50020
33	0.41679	-0.50222	34	0.41496	-0.50381	35	0.41278	-0.50483	36	0.41039	-0.50521
37	0.40799	-0.50491	38	0.40577	-0.50396	39	0.40390	-0.50243	40	0.40252	-0.50045
41	0.38701	-0.47026	42	0.37080	-0.44003	43	0.35399	-0.41008	44	0.33658	-0.38046
45	0.31854	-0.35120	46	0.29983	-0.32234	47	0.28043	-0.29392	48	0.26032	-0.26600
49	0.23946	-0.23863	50	0.21783	-0.21186	51	0.19540	-0.18577	52	0.17214	-0.16042
53	0.14801	-0.13591	54	0.12298	-0.11234	55	0.09701	-0.08983	56	0.07006	-0.06854
57	0.04207	-0.04865	58	0.01301	-0.03041	59	-0.01716	-0.01411	60	-0.04845	-0.00014
61	-0.08081	0.01103	62	-0.11411	0.01886	63	-0.14807	0.02275	64	-0.18222	0.02222
65	-0.21595	0.01697	66	-0.24861	0.00708	67	-0.27964	-0.00706	68	-0.30835	-0.02454
69	-0.31307	-0.02701	70	-0.31822	-0.02834	71	-0.32354	-0.02843	72	-0.32874	-0.02731
73	-0.33355	-0.02501	74	-0.33769	-0.02167	75	-0.34095	-0.01747	76	-0.34317	-0.01263
77	-0.34420	-0.00741	78	-0.34401	-0.00209						

Table 9 Subscale HTF turbine rig rotor coordinates - mean

Planar Slice Radius = 2.8338 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.31974	0.03224	2	-0.30201	0.06860	3	-0.27964	0.10294	4	-0.25260	0.13372
5	-0.22088	0.15963	6	-0.18495	0.17923	7	-0.14582	0.19113	8	-0.10507	0.19428
9	-0.06464	0.18823	10	-0.02647	0.17342	11	0.00820	0.15144	12	0.03915	0.12426
13	0.06686	0.09359	14	0.09215	0.06074	15	0.11584	0.02657	16	0.13858	-0.00832
17	0.16080	-0.04361	18	0.18266	-0.07916	19	0.20417	-0.11493	20	0.22532	-0.15089
21	0.24611	-0.18700	22	0.26656	-0.22322	23	0.28664	-0.25953	24	0.30638	-0.29588
25	0.32576	-0.33224	26	0.34479	-0.36859	27	0.36348	-0.40489	28	0.38181	-0.44110
29	0.39970	-0.47701	30	0.40044	-0.47925	31	0.40053	-0.48160	32	0.39996	-0.48389
33	0.39879	-0.48593	34	0.39709	-0.48756	35	0.39501	-0.48866	36	0.39271	-0.48914
37	0.39036	-0.48897	38	0.38815	-0.48815	39	0.38626	-0.48675	40	0.38482	-0.48489
41	0.36864	-0.45665	42	0.35234	-0.42903	43	0.33560	-0.40150	44	0.31840	-0.37411
45	0.30072	-0.34687	46	0.28254	-0.31984	47	0.26385	-0.29305	48	0.24461	-0.26655
49	0.22481	-0.24038	50	0.20442	-0.21462	51	0.18341	-0.18931	52	0.16174	-0.16453
53	0.13939	-0.14035	54	0.11630	-0.11688	55	0.09244	-0.09422	56	0.06775	-0.07251
57	0.04218	-0.05190	58	0.01567	-0.03260	59	-0.01185	-0.01486	60	-0.04042	0.00099
61	-0.07007	0.01454	62	-0.10078	0.02528	63	-0.13239	0.03261	64	-0.16460	0.03591
65	-0.19688	0.03463	66	-0.22855	0.02857	67	-0.25893	0.01789	68	-0.28712	0.00338
69	-0.29189	0.00124	70	-0.29702	0.00024	71	-0.30225	0.00044	72	-0.30729	0.00181
73	-0.31190	0.00430	74	-0.31581	0.00776	75	-0.31884	0.01203	76	-0.32082	0.01687
77	-0.32165	0.02203	78	-0.32128	0.02725						

Table 10 Subscale HTF turbine rig rotor coordinates - 75% span

Planar Slice Radius = 3.0698 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.29449	0.05380	2	-0.27853	0.08686	3	-0.25745	0.11781	4	-0.23158	0.14485
5	-0.20123	0.16667	6	-0.16718	0.18196	7	-0.13069	0.18956	8	-0.09345	0.18870
9	-0.05741	0.17923	10	-0.02434	0.16191	11	0.00505	0.13868	12	0.03118	0.11164
13	0.05504	0.08239	14	0.07761	0.05198	15	0.09955	0.02100	16	0.12116	-0.01030
17	0.14248	-0.04188	18	0.16349	-0.07370	19	0.18419	-0.10574	20	0.20456	-0.13799
21	0.22461	-0.17040	22	0.24432	-0.20295	23	0.26368	-0.23562	24	0.28268	-0.26837
25	0.30132	-0.30119	26	0.31960	-0.33403	27	0.33749	-0.36687	28	0.35500	-0.39969
29	0.37201	-0.43224	30	0.37280	-0.43450	31	0.37294	-0.43688	32	0.37241	-0.43921
33	0.37126	-0.44130	34	0.36958	-0.44300	35	0.36749	-0.44416	36	0.36517	-0.44471
37	0.36278	-0.44459	38	0.36052	-0.44381	39	0.35857	-0.44245	40	0.35706	-0.44059
41	0.34165	-0.41542	42	0.32597	-0.39072	43	0.30981	-0.36618	44	0.29317	-0.34182
45	0.27605	-0.31767	46	0.25845	-0.29375	47	0.24038	-0.27008	48	0.22184	-0.24671
49	0.20283	-0.22364	50	0.18334	-0.20093	51	0.16338	-0.17859	52	0.14295	-0.15667
53	0.12203	-0.13520	54	0.10061	-0.11424	55	0.07866	-0.09386	56	0.05617	-0.07412
57	0.03310	-0.05512	58	0.00938	-0.03698	59	-0.01502	-0.01988	60	-0.04018	-0.00402
61	-0.06618	0.01031	62	-0.09307	0.02271	63	-0.12087	0.03268	64	-0.14952	0.03957
65	-0.17875	0.04262	66	-0.20804	0.04118	67	-0.23664	0.03491	68	-0.26341	0.02419
69	-0.26816	0.02249	70	-0.27317	0.02187	71	-0.27820	0.02237	72	-0.28299	0.02395
73	-0.28732	0.02655	74	-0.29097	0.03003	75	-0.29378	0.03423	76	-0.29559	0.03894
77	-0.29633	0.04393	78	-0.29596	0.04897						

Table 11 Subscale HTF turbine rig rotor coordinates - tip

Planar Slice Radius = 3.3058 inches

PT	X	Y	PT	X	Y	PT	X	Y	PT	X	Y
1	-0.24588	0.12075	2	-0.22563	0.14457	3	-0.20053	0.16389	4	-0.17202	0.17745
5	-0.14140	0.18467	6	-0.11007	0.18530	7	-0.07939	0.17941	8	-0.05066	0.16732
9	-0.02508	0.14957	10	-0.00374	0.12690	11	0.01402	0.10120	12	0.03143	0.07516
13	0.04867	0.04892	14	0.06571	0.02249	15	0.08254	-0.00412	16	0.09913	-0.03087
17	0.11547	-0.05777	18	0.13155	-0.08477	19	0.14733	-0.11187	20	0.16281	-0.13903
21	0.17797	-0.16623	22	0.19279	-0.19344	23	0.20724	-0.22064	24	0.22132	-0.24779
25	0.23500	-0.27487	26	0.24828	-0.30186	27	0.26113	-0.32872	28	0.27355	-0.35542
29	0.28537	-0.38160	30	0.28604	-0.38392	31	0.28604	-0.38633	32	0.28538	-0.38865
33	0.28410	-0.39070	34	0.28231	-0.39231	35	0.28015	-0.39338	36	0.27778	-0.39381
37	0.27538	-0.39356	38	0.27314	-0.39267	39	0.27123	-0.39120	40	0.26980	-0.38926
41	0.25848	-0.36877	42	0.24639	-0.34795	43	0.23378	-0.32722	44	0.22066	-0.30661
45	0.20704	-0.28612	46	0.19296	-0.26576	47	0.17844	-0.24554	48	0.16350	-0.22548
49	0.14816	-0.20556	50	0.13245	-0.18580	51	0.11639	-0.16621	52	0.09999	-0.14678
53	0.08327	-0.12754	54	0.06624	-0.10849	55	0.04890	-0.08965	56	0.03123	-0.07105
57	0.01323	-0.05273	58	-0.00514	-0.03473	59	-0.02391	-0.01713	60	-0.04314	-0.00001
61	-0.06290	0.01650	62	-0.08330	0.03222	63	-0.10445	0.04690	64	-0.12650	0.06017
65	-0.14960	0.07149	66	-0.17384	0.08004	67	-0.19910	0.08472	68	-0.22474	0.08433
69	-0.22958	0.08428	70	-0.23432	0.08524	71	-0.23875	0.08718	72	-0.24268	0.09000
73	-0.24593	0.09358	74	-0.24836	0.09776	75	-0.24985	0.10236	76	-0.25035	0.10717
77	-0.24984	0.11198	78	-0.24832	0.11658						

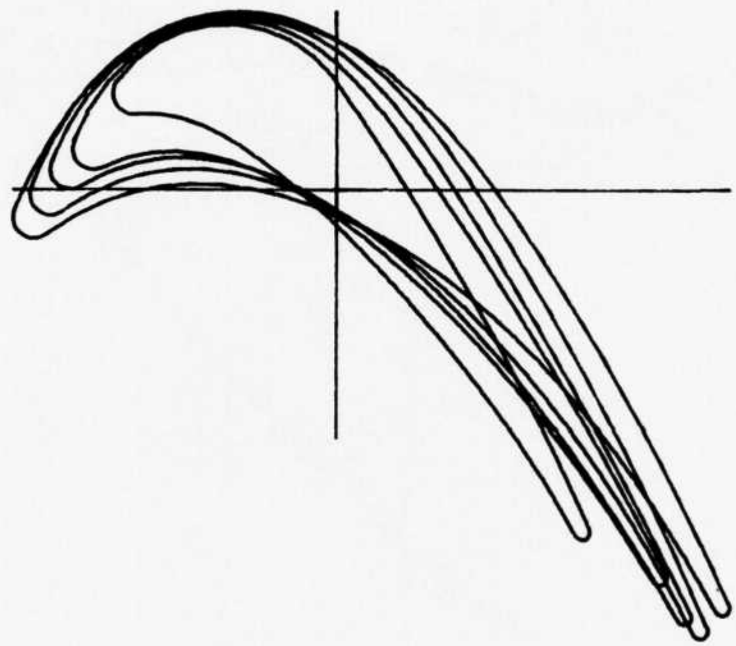


Figure 10 Subscale HTF turbine blade section composite

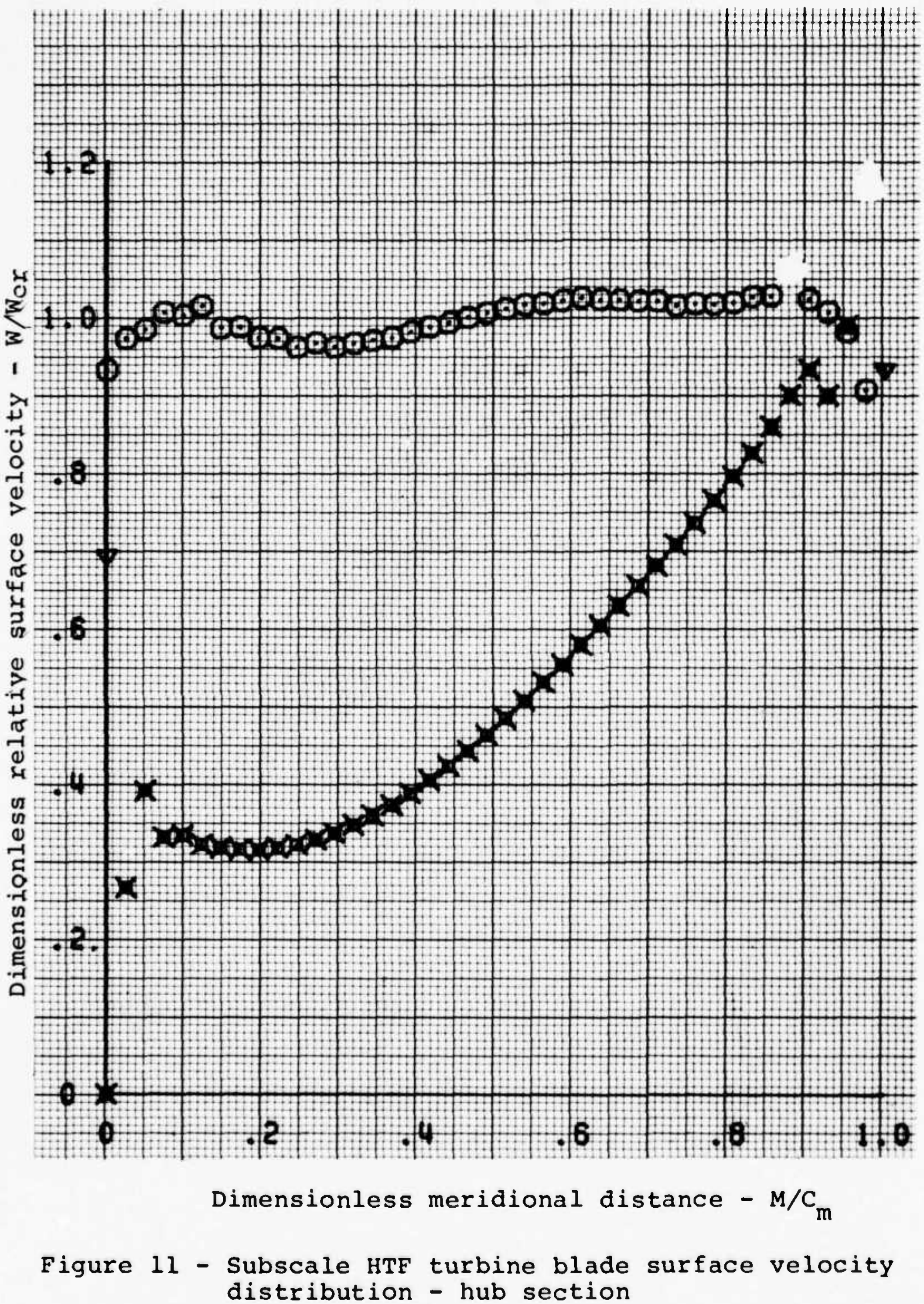


Figure 11 - Subscale HTF turbine blade surface velocity distribution - hub section

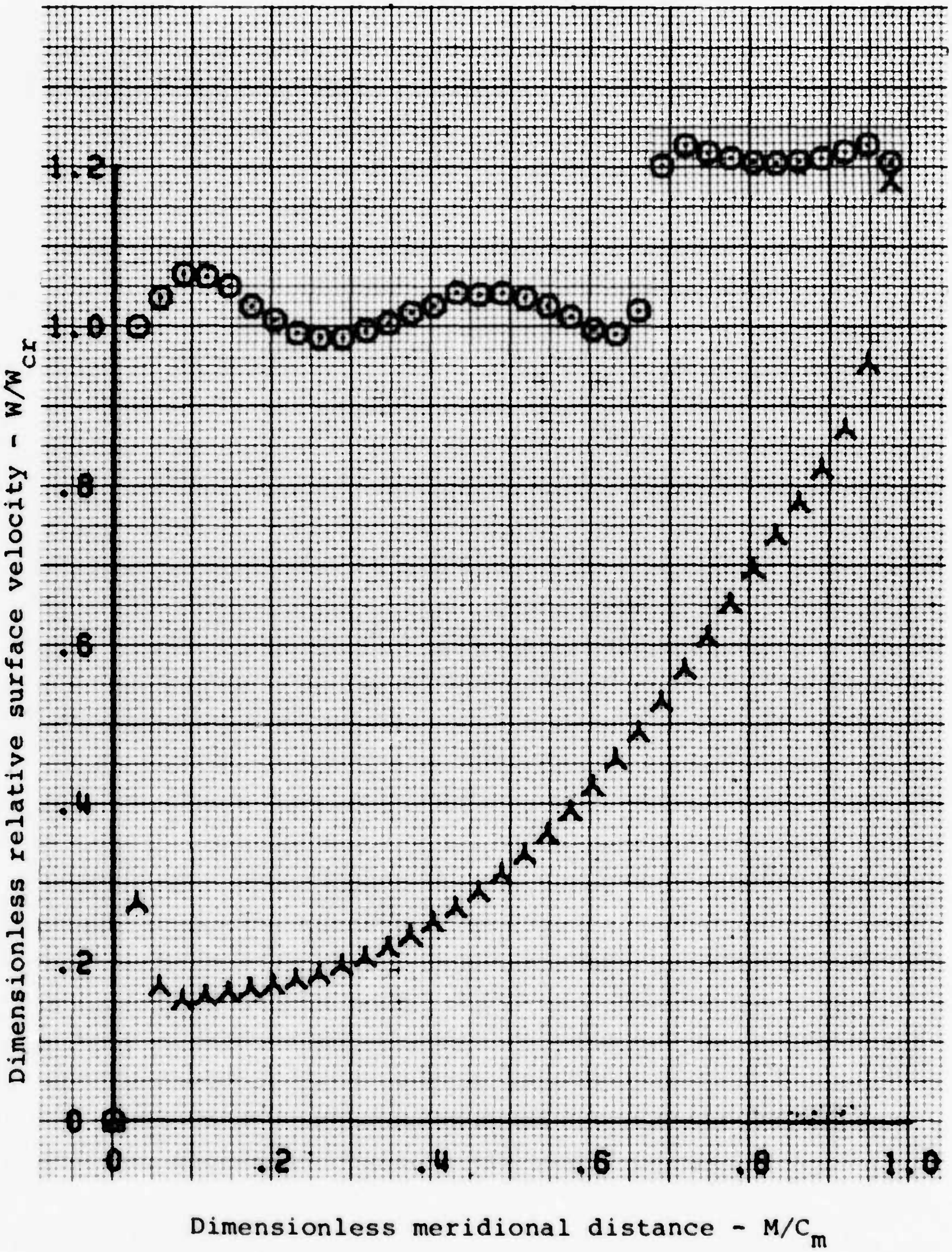


Figure 12 Subscale HTF turbine blade surface velocity distribution - mean section

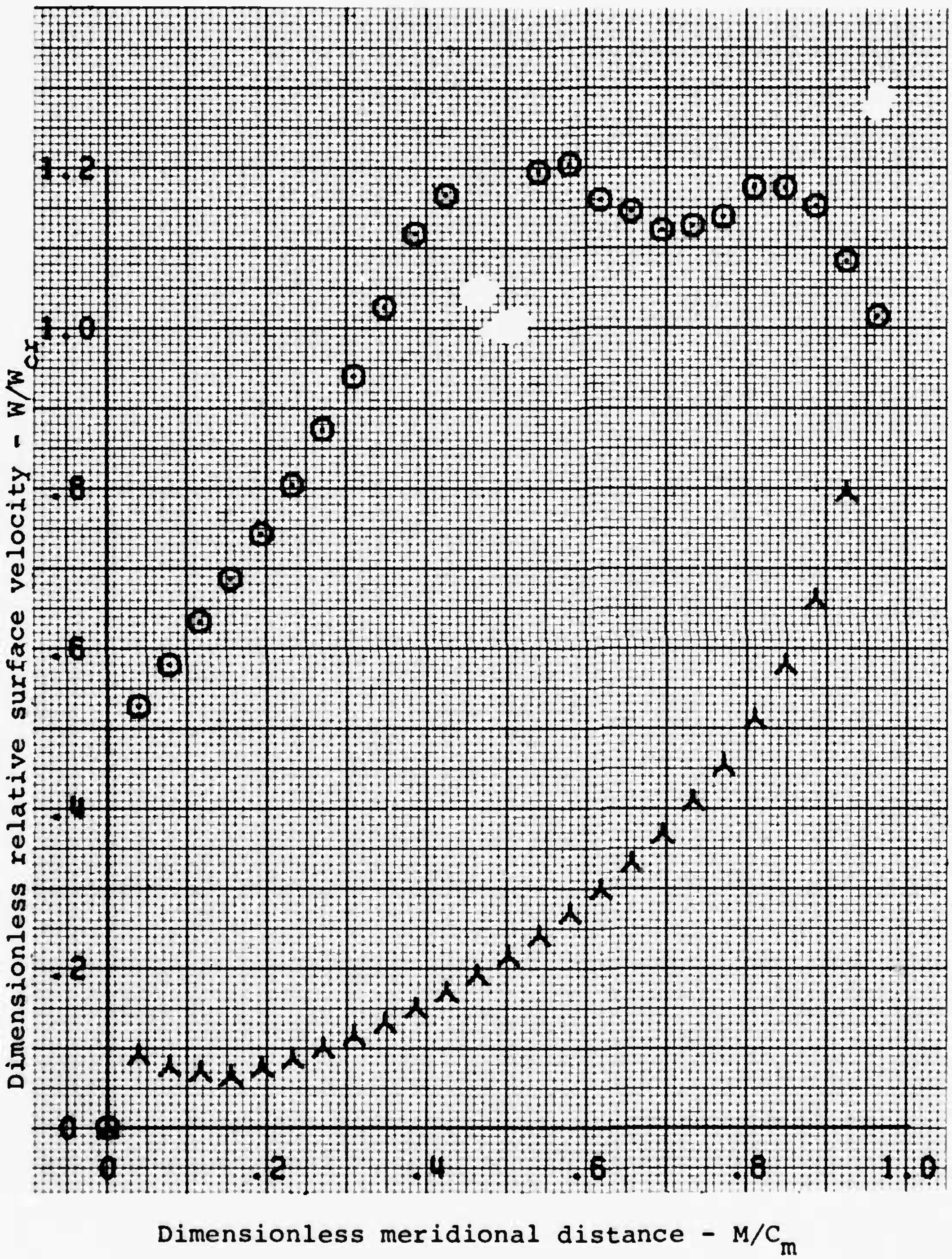


Figure 13 Subscale HTF turbine blade surface velocity distribution - tip section

SECTION VI

SUBSCALE HTF TURBINE RIG FABRICATION

The subscale turbine was fabricated from materials suitable for cold air rig testing. The vane and blade assemblies were both machined from stainless steel. The stator assembly was fabricated by machining the vanes and inner rig from an AMS 5646 forging. This provided a part which formed an integral vane and inner band (hub flowpath). The outer band (tip flowpath) was machined as a separate part. The stator assembly was fabricated by brazing the outer band to the vane tips. This fabrication philosophy has been used previously by DDA and is preferred to machining the individual vanes and attaching them to separate inner and outer bands. The method employed is not only cost effective, but it has resulted in a vane assembly which has very consistent vane-to-vane throat dimensions and setting angles. Table 12 shows the measured throat dimensions at approximately 20 and 80 percent span location. The average measured throat dimension at these radial locations are 0.196 and 0.219 compared to the design values of 0.197 and 0.226 at the same radial locations, respectively.

The rotor blades and wheel were fabricated in much the same manner as the integral vane - inner band. They were machined from a single AMS 5613 forging, resulting in an integral wheel-blading part. This single piece fabrication procedure resulted

Table 12 Measured subscale HTF turbine rig vane throat dimensions

Passage	Throat - Inches 5.125ϕ	6.221ϕ	Passage	Throat - inches 5.125ϕ	6.221ϕ
1	.197	.217	13	.196	.221
2	.195	.216	14	.193	.219
3	.195	.217	15	.194	.219
4	.195	.217	16	.196	.219
5	.194	.216	17	.196	.222
6	.196	.219	18	.194	.218
7	.196	.219	19	.194	.220
8	.195	.219	20	.195	.221
9	.199	.221	21	.198	.221
10	.198	.216	22	.195	.221
11	.200	.227	23	.195	.218
12	.197	.221	24	.195	.219

Table 13 Measured subscale HTF turbine rig rotor throat dimensions

Passage	Throat - Inches 5.200ϕ	6.400ϕ	Passage	Throat - inches 5.200ϕ	6.400ϕ
1	.232	.314	16	.232	.313
2	.233	.312	17	.233	.314
3	.233	.313	18	.233	.312
4	.232	.313	19	.233	.312
5	.233	.312	20	.232	.313
6	.233	.313	21	.232	.312
7	.232	.314	22	.233	.312
8	.232	.313	23	.234	.313
9	.233	.313	24	.234	.313
10	.233	.314	25	.233	.314
11	.233	.313	26	.233	.313
12	.232	.313	27	.234	.314
13	.233	.314	28	.233	.314
14	.233	.314	29	.233	.313
15	.233	.313	30	.232	.314

in accurate blading which exhibited little deviation in the throat dimensions and setting angles. Table 13 shows the measured throat dimensions for all 30 blade passages at 26 and 89 percent span locations. The design values for these locations are 0.235 and 0.329 inches. The measured average throat dimension for these radial locations are 0.233 and 0.313 inches.

These measurements of the subscale HTF turbine hardware indicated that both airfoil rows were fabricated slightly closed in the near tip radial locations. However, the measurements were essentially the same as design values at approximately 20-25 percent position.

SECTION VII

SUBSCALE HTF TURBINE RIG TEST PLAN

The subscale HTF turbine testing was conducted in the DDA Small Turbine Research Facility. The testing was conducted in two phases:

Phase I   Stator Annular Cascade Loss Evaluation

Phase II   Overall Turbine Performance Evaluation.

The stator annular cascade testing consisted of a series of four radial-circumferential surveys to define the vane performance over a broad range of exit Mach numbers. Upon completion of Phase I, the rotor was installed and turbine performance mapping was conducted. During Phase II rotor exit radial surveys were also conducted at four selected operating conditions. A detailed description of each test phase follows.

Phase I Stator Annular Cascade Test

The objective of the Phase I testing was to isolate and define the distribution and/or location of aerodynamic losses in the HTF stator. The initial phase of the test program consists of replacing the rotor assembly with a cylindrical spacer to form a constant annular passage downstream of the stator cascade. The stator axial location was the same for both test phases to assure geometric consistency. The vane instrumentation was the same as used during the overall turbine performance evaluation.

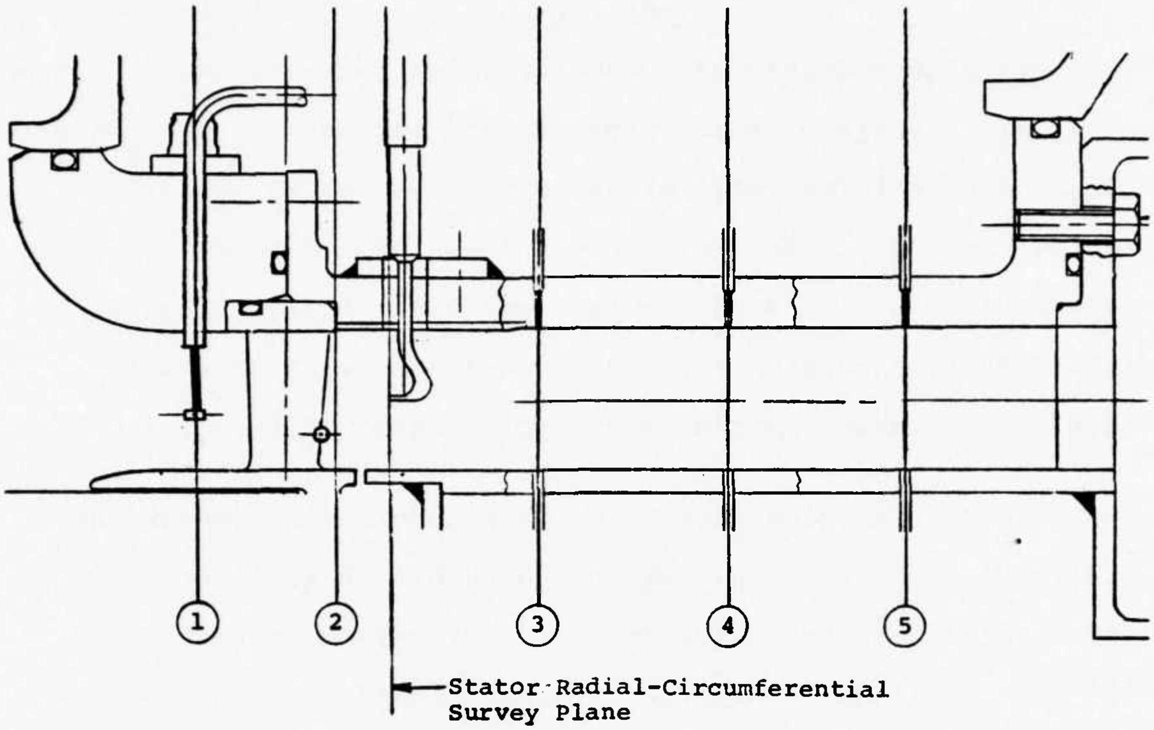
Test Plan

The test plan consists of conducting four radial-circumferential vane exit surveys of total pressure and gas angle over a wide range of vane inlet total pressure to exit static pressure ratios (P_{T1}/P_{S2}). The exit surveys were conducted at (P_{T1}/P_{S2}) values of 1.2, 1.5, 2.26 (design) and 2.4. These values of total/static expansion ratio are consistent with vane exit ideal Mach numbers ranging from approximately 0.5 to 1.2.

The vane exit surveys were taken at eleven radial depths and covered a 20 degree arc. Since the number of vanes are 24 (15 degrees between vanes) the probe traversed approximately 1.3 vane spacings. The probe was positioned in such a manner that measurements were taken across two vane wakes.

Instrumentation

Figure 14 shows the axial location of the stator annular cascade instrumentation. The rig inlet instrumentation consisted of four total pressure Kiel probes equally spaced in the circumferential direction and located in the centers of equal annulus areas. Inlet hub, mean and tip thermocouple elements were positioned at four equally spaced circumferential locations. Five static pressure taps are verniered across the vane passage in the vane exit plane at both hub and tip locations. An additional three mid-channel static pressure taps are equally spaced circumferentially at hub and tip locations. The radial-circumferential vane exit surveys



STATION NO.	T_T	P_T	P_S	α
1	4-3 Element rakes	4 Keil probes		
2			8 Wall taps hub, tip	
3			5 Wall taps hub, tip	
4			5 Wall taps hub, tip	
5			1 Wall tap hub, tip	
Vane Survey		X		X

Figure 14 Instrumentation schematic for the subscale HTF stator full annular cascade test

were conducted with a 0.032 inch "cobra" probe which was calibrated to measure total pressure and local gas angle. Exit downstream static pressure taps were located as shown by the instrumentation schematic. Stations 3 and 4 have five static pressure taps at both hub and tip locations. These taps are circumferentially spaced to cover a vane spacing. The far-downstream station has a single static pressure measurement at hub and tip. In addition, airflow rate was measured using an ASME thin plate orifice upstream of the rig inlet plenum.

Data Reduction

The stator annular cascade exit survey data were taken every 0.5 degrees over the 20 degree circumferential traverse for each of the eleven radial depths. Thus, measurements of local total pressure and gas angle were conducted at 440 discrete positions along the vane exit plane. These data were employed to conduct a detailed performance evaluation of the HTF vane in terms of kinetic energy loss coefficient for each of the four total/static expansion ratios investigated.

The definition of the vane kinetic energy loss coefficient at a point in the flow field is:

$$e = 1-\left(\frac{V_{act}}{V_{ideal}}\right)^2 = \frac{\left(\frac{P_{T_1}}{P_{T_S}}\right)^{\frac{\gamma-1}{\gamma}} -1}{\left(\frac{P_{T_1}}{P_{S_S}}\right)^{\frac{\gamma-1}{\gamma}} -1}$$

The vane exit survey plane total pressure (P_{T_S}) was determined using a calibrated "cobra" probe. The local value of survey plane static pressure (P_{S_S}) was assumed to be a linear interpolation of the average hub and tip static pressures at instrumentation station 3. Figures 15 through 18 present the calculated contour maps of the vane kinetic energy loss coefficient (e) for each of the four total/static expansion ratios investigated.

The radial distribution of HTF vane kinetic energy loss coefficient was calculated by mass averaging the definition of e over a one vane spacing.

$$\bar{e}_r = \frac{\int_{\theta_1}^{\theta_2} \rho_s V_{sin}\, \alpha\, e\, r d\theta}{\int_{\theta_1}^{\theta_2} \rho_s V_{sin}\, \alpha\, e\, r d\theta}$$

Figures 19 through 22 present the calculated radial distributions of $\bar{e}_r$ for the vane total/static expansion ratios of 1.2, 1.5, 2.26 (design) and 2.4, respectively.

The vane passage overall loss coefficient ($\bar{e}$) was calculated by mass averaging the radial distribution of $\bar{e}_r$ over the vane exit height.

$$\bar{e} = \frac{\int_{r_h}^{r_t} \rho_s V_{sin}\, \alpha\, \bar{e}_r\, rdr}{\int_{r_h}^{r_t} \rho_s V_{sin}\, \alpha\, rdr}$$

view looking downstream

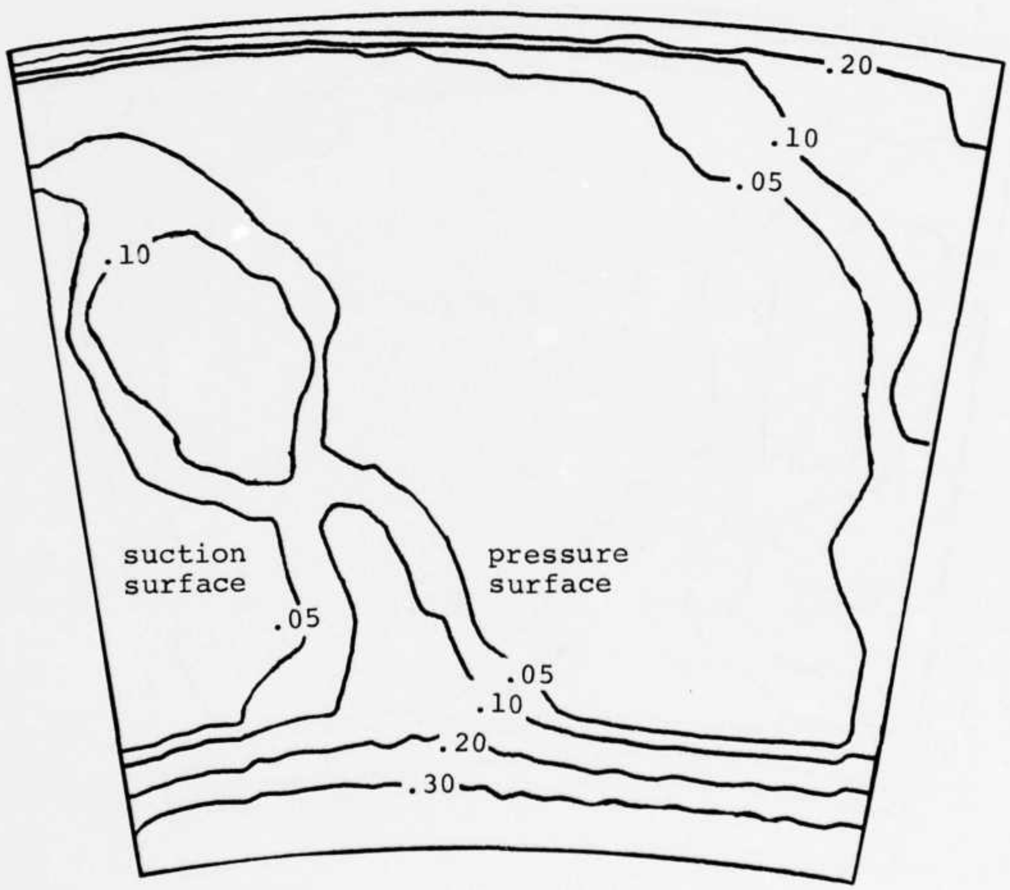


Figure 15 Subscale HTF turbine vane kinetic energy loss coefficient contour map - $R_{e_{TS}} = 1.20$

view looking downstream

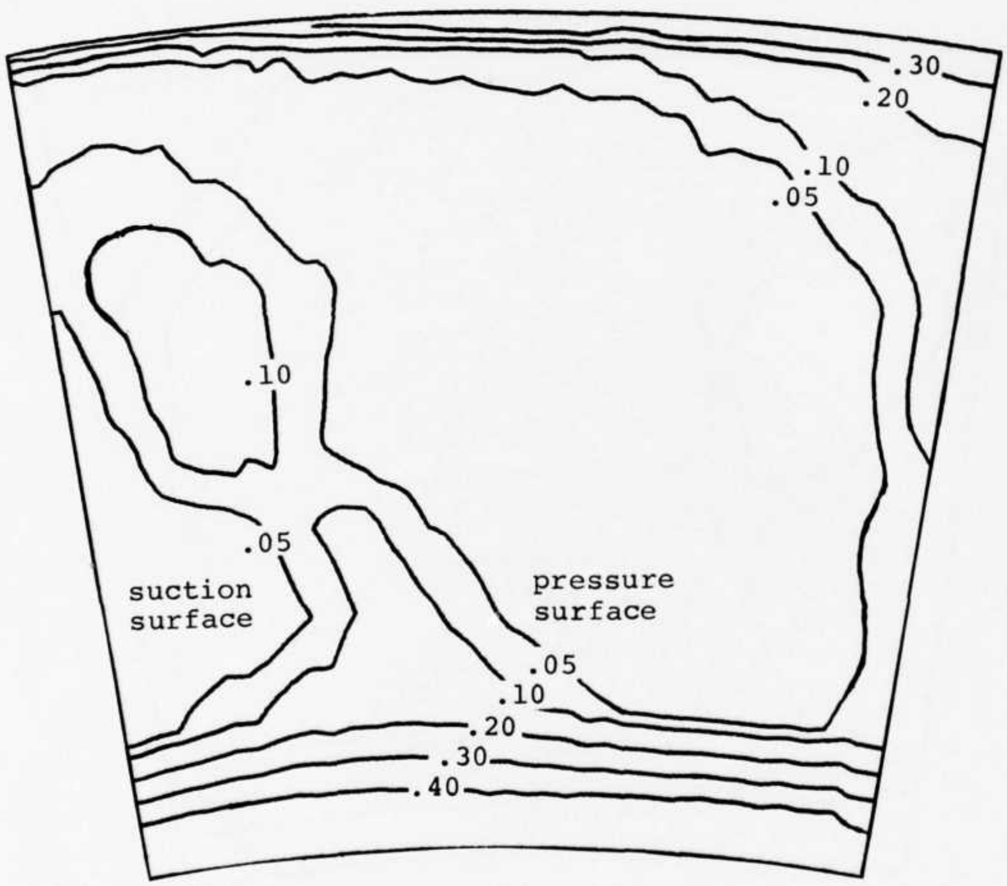


Figure 16 Subscale HTF turbine vane kinetic energy loss coefficient contour map - $R_{e_{TS}} = 1.5$

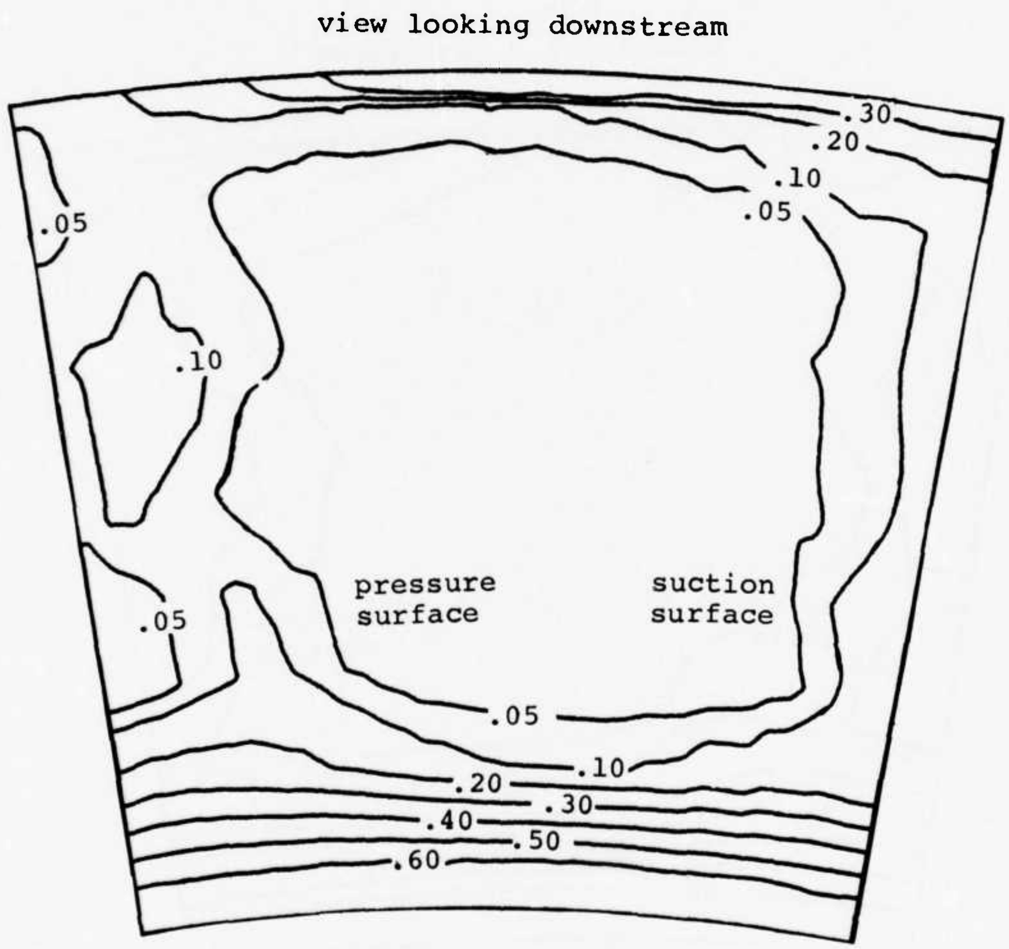


Figure 17 Subscale HTF turbine vane kinetic energy loss coefficient contour map - $R_{e_{TS}} = 2.26$

view looking downstream

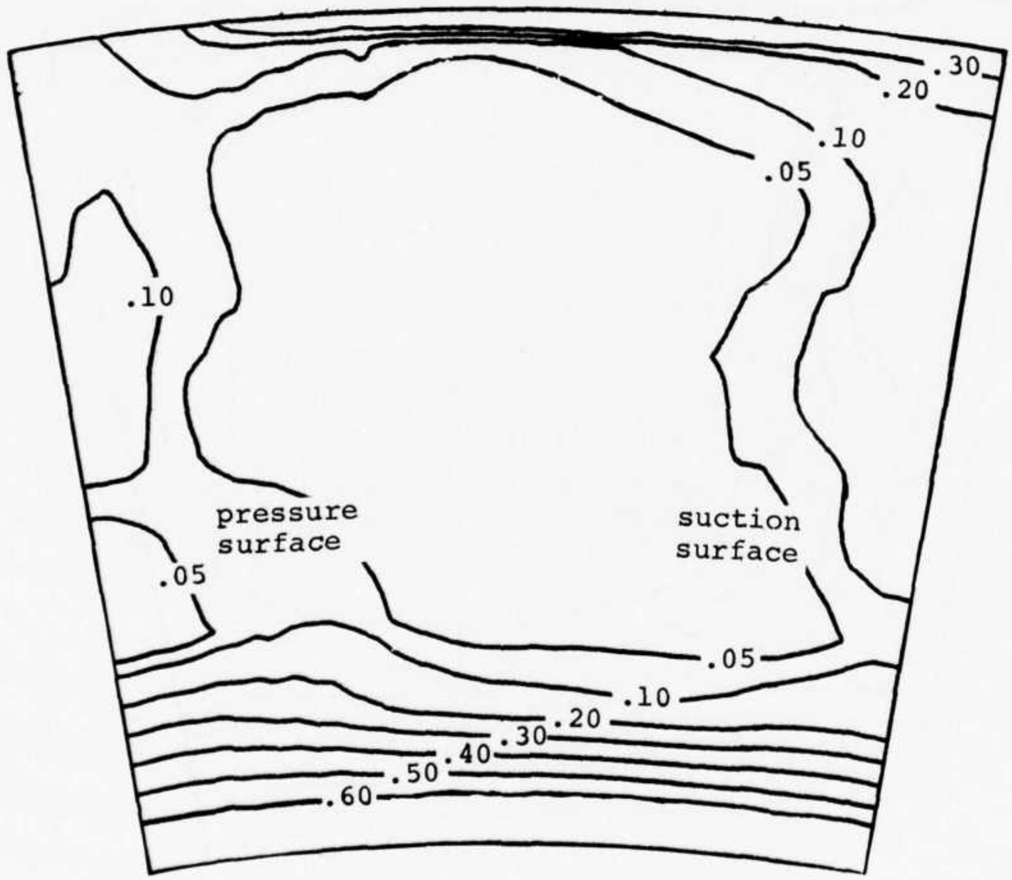


Figure 18 Subscale HTF turbine vane kinetic energy loss coefficient contour map - $R_{e_{TS}} = 2.40$

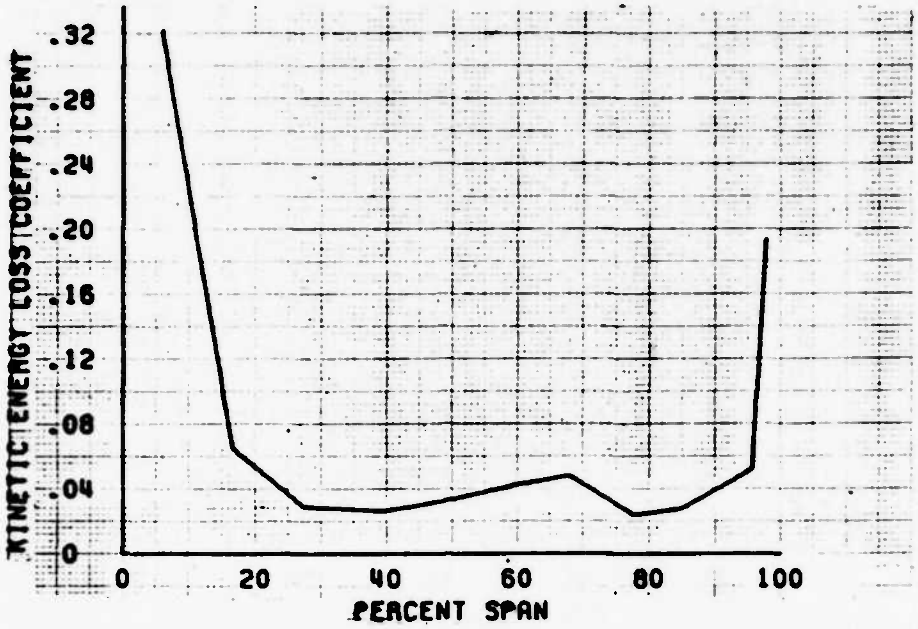


Figure 19 Radial distribution of vane $\bar{e}$ - $R_{e_{TS}}$ = 1.20

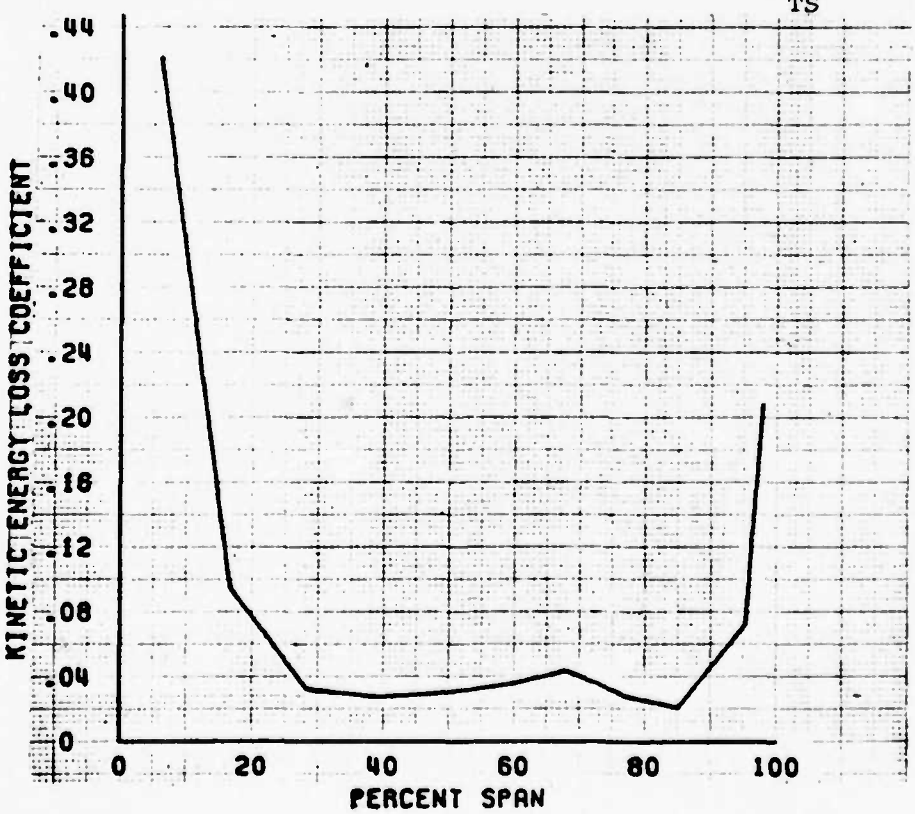


Figure 20 Radial distribution of vane $\bar{e}$ - $R_{e_{TS}}$ = 1.50

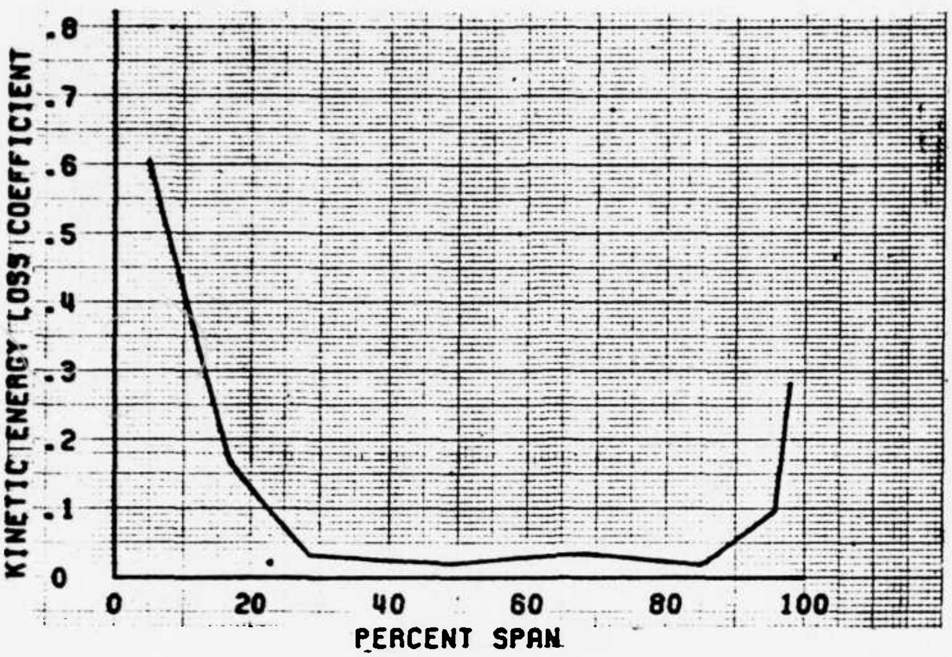


Figure 21   Radial distribution of vane $\bar{e}_r$ - $R_{e_{TS}}$ = 2.26

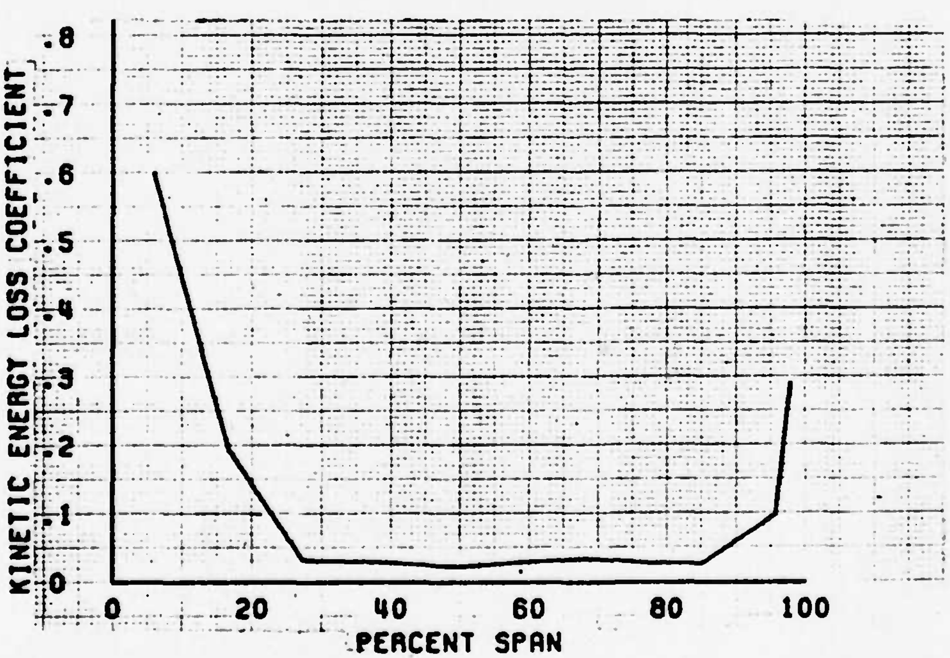


Figure 22   Radial distribution of vane $\bar{e}_r$ - $R_{e_{TS}}$ = 2.40

Figure 23 shows the calculated vane overall loss coefficient ($\bar{e}$) as a function of exit actual Mach number. The value of $\bar{e}$ used for the aerodynamic design of the subscale HTF turbine is also shown.

The measured relationship between stator inlet equivalent mass flow rate $\frac{(\dot{m}\sqrt{\theta_{cr}}\varepsilon)}{\delta}$ and vane total/static expansion ratio is shown by Figure 24. The design point value of this parameter is shown for reference.

Data Analysis

The HTF subscale vane annular cascade exhibited relatively high losses in the hub endwall region over the entire range of total/static expansion ratios investigated. An examination of the loss contour plots indicates that these losses are essentially independent of circumferential position. The axisymmetric characteristics of the hub loss contours suggest that the airfoil is not the primary source of this loss mechanism. It is thought that these losses are the result of a relatively thick boundary layer build-up upstream of the vane annular cascade.

Due to torque and dynamometer power limitations on the DDA Small Turbine Research Facility, the HTF turbine hub diameter was set as low as mechanically possible. This minimum diameter was established by the turbine rig rotor shaft housing. As a result, the hub geometry upstream of the vane

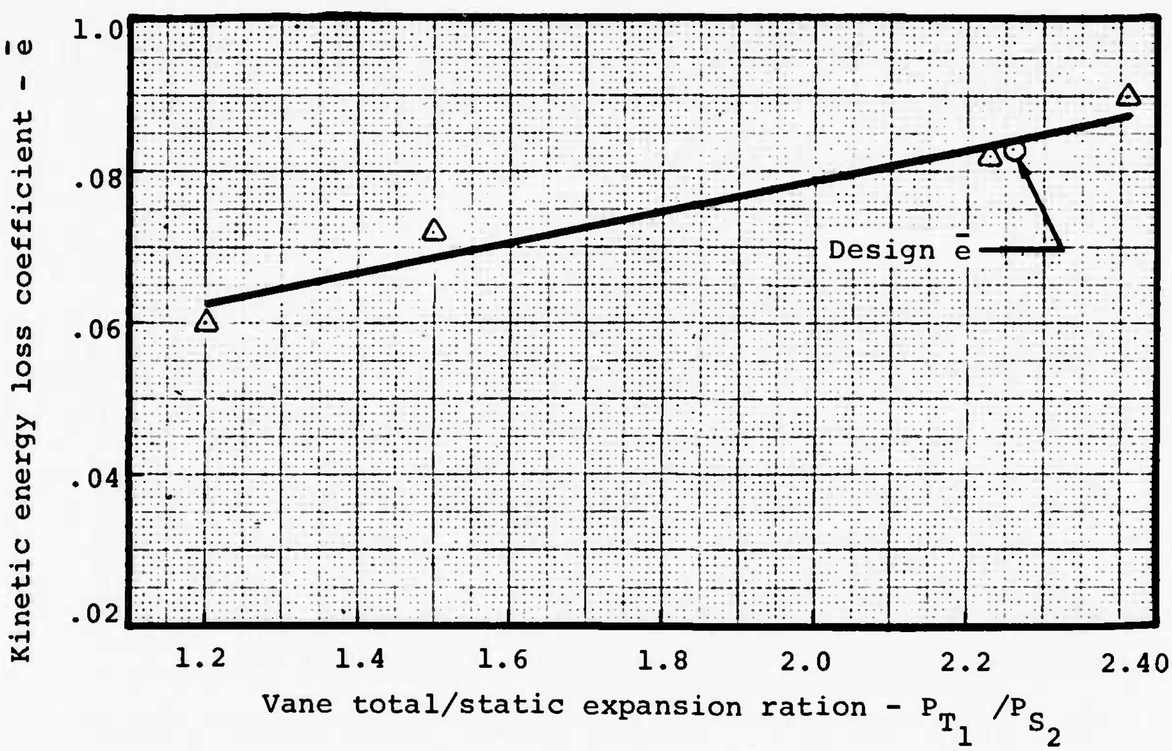


Figure 23 Relationship between measured $\bar{e}$ and vane total/static expansion ratio

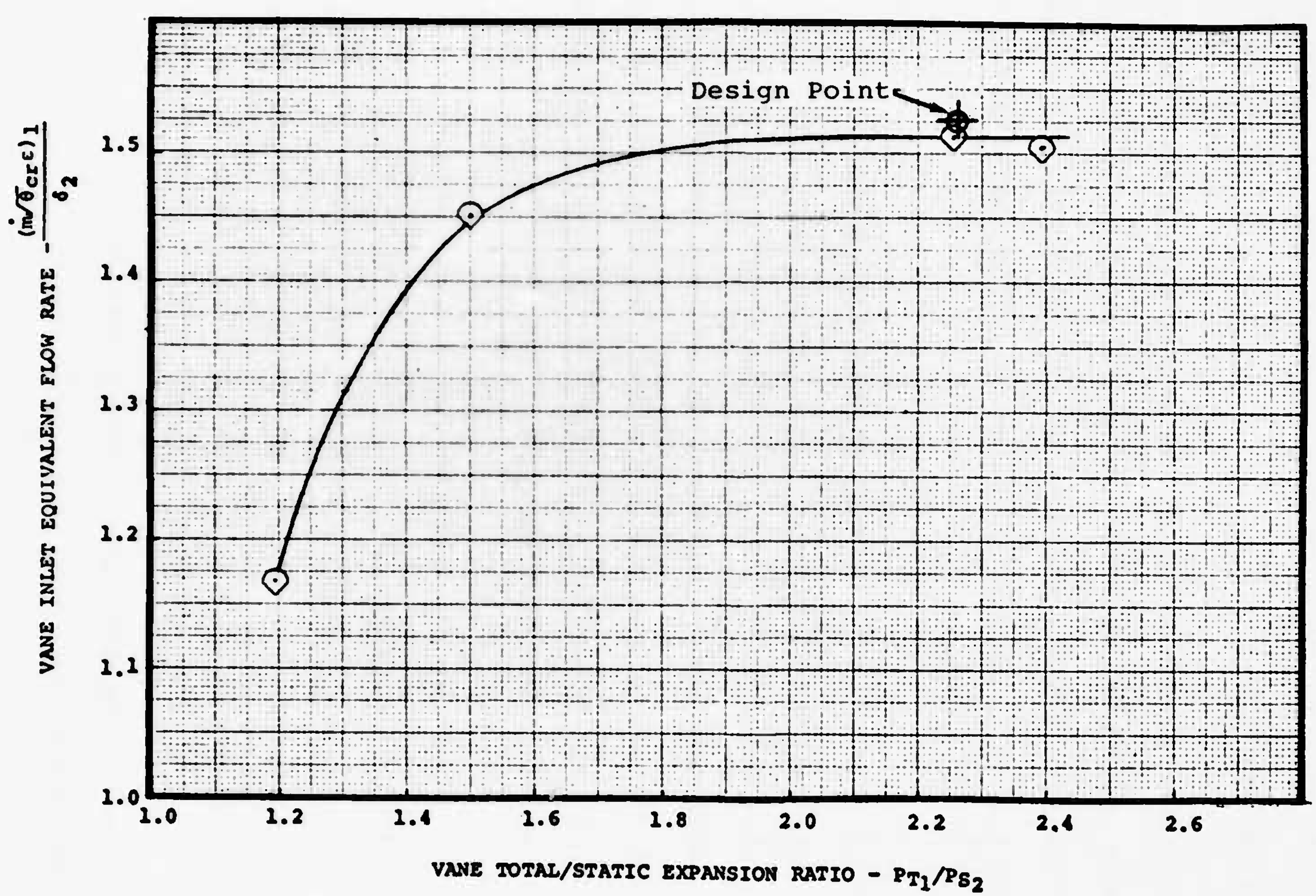


Figure 24 Subscale HTF turbine vane measured flow rate characteristics

is cylindrical. This extended upstream of the vane hub is thought to provide an excessive boundary layer build-up. It should be noted that the rig tip employs a conventional inlet bellmouth.

The measured design point equivalent flow rate of 1.511 compares very well with the design value of 1.525. As was previously discussed, measurements of the actual rig hardware showed the vane throats to be fabricated slightly closed in the near tip region.

Phase II Overall Turbine Performance Evaluation

Upon completion of the stator full annular cascade tests, the stator exit survey probe and downstream constant annulus area spacer was removed and the rotor assembly was installed without disturbing the vane assembly. The objective of Phase II testing was to conduct a detailed performance evaluation of the subscale HTF turbine rig.

Test Plan

Performance mapping was conducted over a broad range of overall turbine total/total expansion ratios (R_{eTT}) for each of five equivalent speed lines ($N/\sqrt{\theta_{cr}}$). The particular speed lines considered were 70, 80, 90, 100 and 110 percent of design point equivalent speed. The discrete steady state points considered in the development of the subscale HTF turbine performance map are shown by Table 14.

TABLE 14

Schematic of HTF Subscale Turbine Performance Testing

Nominal Re_{TT}	Percent Design Point $N/\sqrt{\theta_{cr}}$				
	70	80	90	100	110
1.4	X	X	X	X	X
1.6	X, 1	X	X	X	X
1.8	X	X	X	X, 1	X
2.0	X	X	X	X	X
2.2	X	X	X	X	X
2.4	X	X	X	1,2,X	X
2.6	X	X	X	X	X
2.8		X	X	X	X
3.0			X	X	X
3.2			X	X, 1	X
3.4				X	X
3.6				X	X
3.8				X	X
3.9				X	
4.0					X
4.1					X

1 - rotor exit survey

2 - aerodynamic design point

Turbine exit radial surveys were performed at four selected operating conditions as denoted by Table 14. The survey was accomplished by using two of the five rotor exit yaw probes. These probes measured the exit total temperature, total pressure and flow angle at centers of nine equal area annuli.

The testing was conducted at a nominal rig inlet temperature of 300°F. Inlet pressure was adjusted to achieve the desired turbine expansion ratios. The turbine speed was controlled

by the facility dynamometer and was adjusted on line to achieve the desired equivalent speed.

Instrumentation

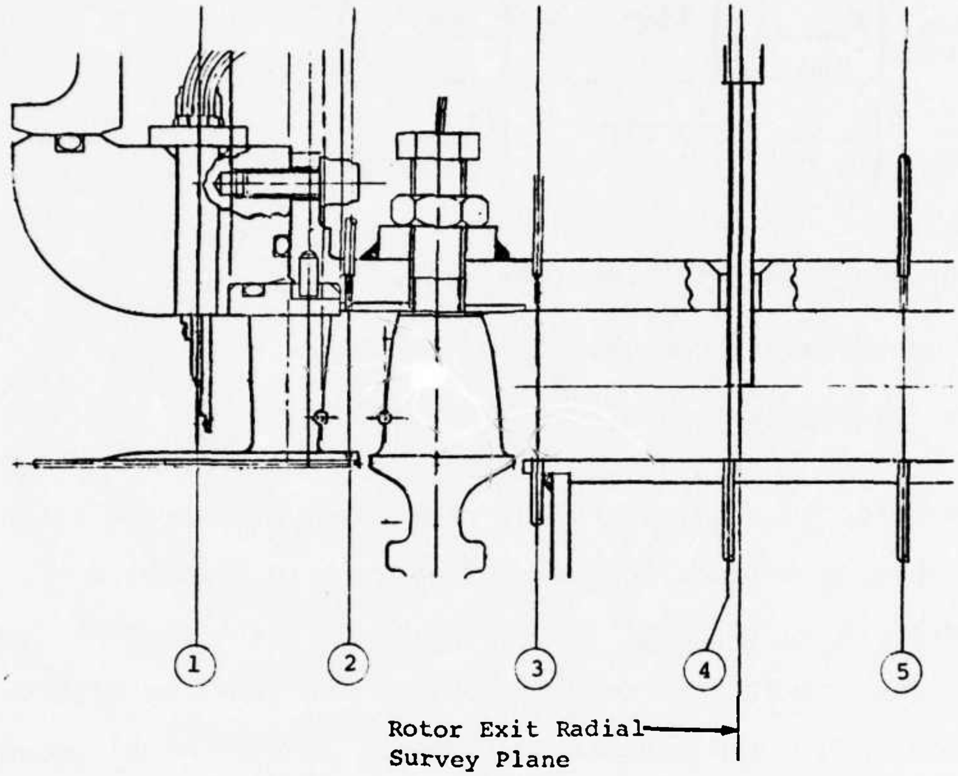
The instrumentation for the overall turbine testing required the additional installation of five yaw probes downstream of the rotor exit plane. The axial position of these probes is noted by the instrumentation schematic shown by Figure 25. These probes nominally are located on the centers of five equal annular areas. Two of these probes were moved radially inward and data recorded over a range of nine radial depths. The instrumentation at stations 1 through 5 remained unaltered between the stator annular and turbine testing.

Data Reduction

The turbine steady state performance was defined using the measured parameters of inlet flow rate ($\dot{m}_1$), inlet total temperature (T_{T_1}), inlet total pressure (P_{T_1}), shaft torque (τ), rotor exit absolute gas angle (α_4), rotor exit static pressure (P_{S_4}) and rotational speed (N). The turbine equivalent flow rate, speed and torque were calculated using the measured values of T_{T_1} and P_{T_1} as:

$$\theta_{cr_1} = \left(\frac{2\gamma g R T_T}{\gamma + 1}\right)_1 \Bigg/ \left(\frac{2\gamma g R T_T}{\gamma + 1}\right)_{Std}$$

$$\delta_1 = \frac{P_{T_1}}{P_{T_{Std}}}$$



STATION NO.	T_T	P_T	P_S	α
1	4-3 Element rakes	4 Keil probes		
2			8 Wall taps hub, tip	
3			5 Wall taps hub, tip	
4			5 Wall taps hub, tip	
5			1 Wall tap hub, tip	
Rotor Survey	X	X		X

Figure 25 Instrumentation schematic for the subscale HTF turbine test

$$\varepsilon = \frac{\left(\frac{2}{\gamma_{Std} + 1}\right)^{\frac{1}{\gamma_{Std} - 1}} \left(\frac{\gamma_{Std}}{\gamma_{Std} + 1}\right)}{\left(\frac{2}{\gamma_1 + 1}\right)^{\frac{1}{\gamma_1 - 1}} \left(\frac{\gamma_1}{\gamma_1 + 1}\right)}$$

- o equivalent turbine flow rate, $\frac{(\dot{m}\sqrt{\theta_{cr}}\,\varepsilon)_1}{\delta}$
- o equivalent torque, $\frac{\tau\varepsilon_1}{\delta_1}$
- o equivalent speed, $N\sqrt{\theta_{cr}}$.

The measured turbine equivalent flow rate, torque and exit angle were correlated in terms of overall total/static expansion ratio (P_{T1}/P_{S4}) for lines of constant percent design equivalent speed. The resulting plots are shown by Figures 26 through 28. The symbols are used to denote actual measured turbine steady state data. The design point value of these parameters are also shown. These measured data were curve fit analytically and used to define all other performance parameters.

Turbine exit total pressure (P_{T4}) was calculated using smoothed values of $\dot{m}_1$, P_{S4}, T_{T4} (calculated from measured torque), α_4 and continuity. Experience at DDA has shown that calculated turbine exit pressures provide more consistent performance characteristics than typically results from using measured P_{T4} values.

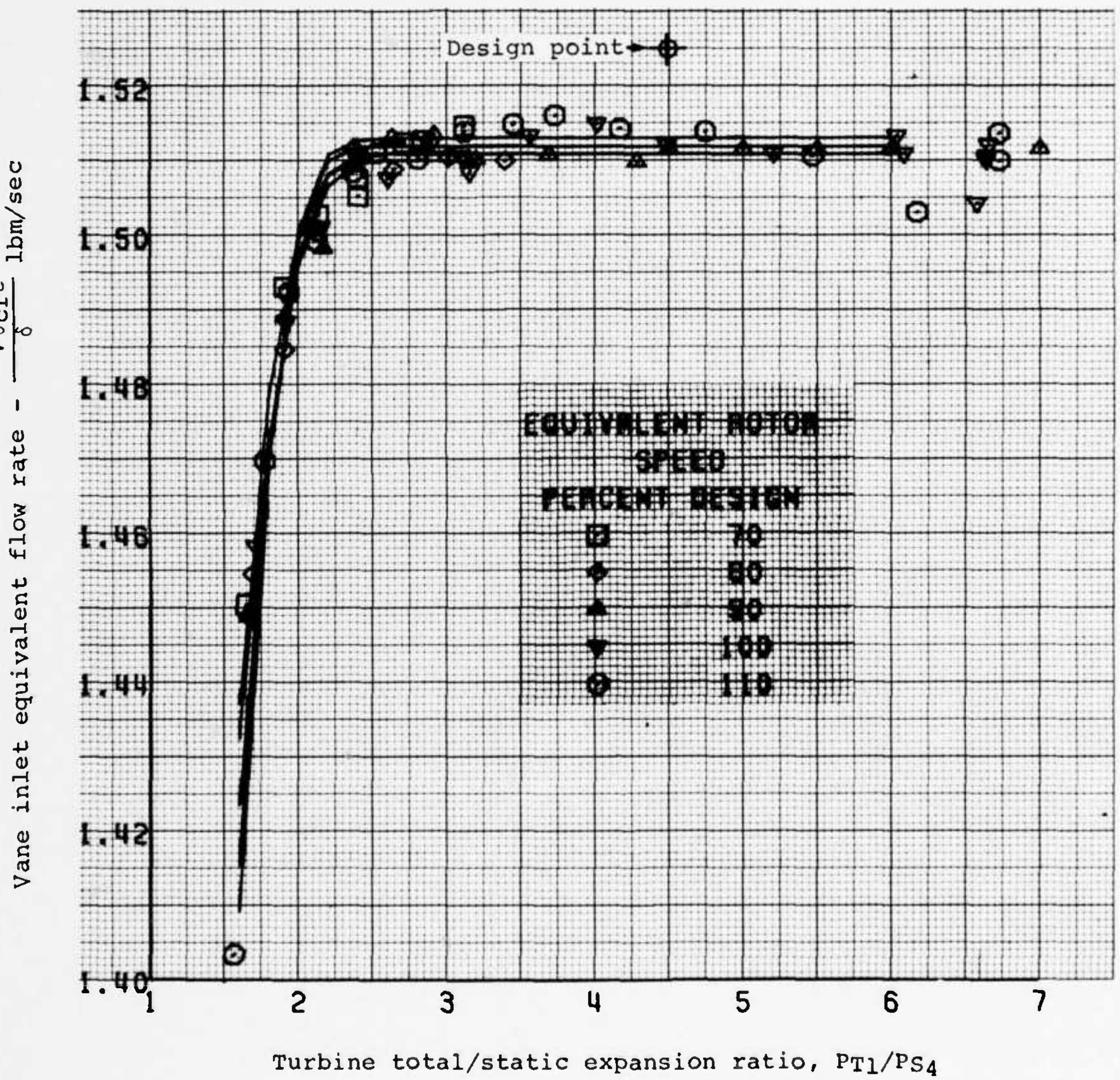


Figure 26 Subscale HTF turbine measured flow rate characteristics

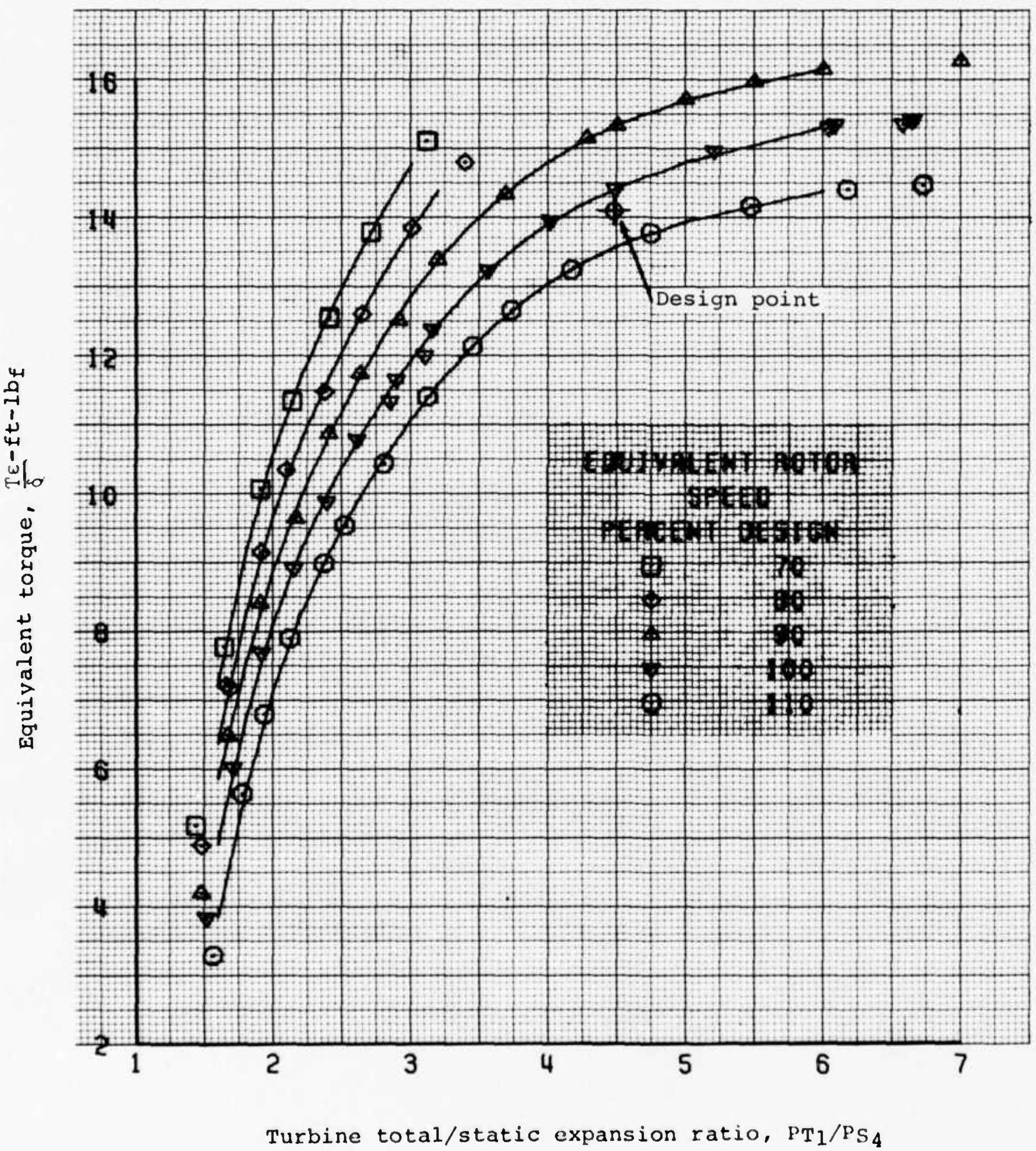


Figure 27 Subscale HTF turbine measured torque characteristics

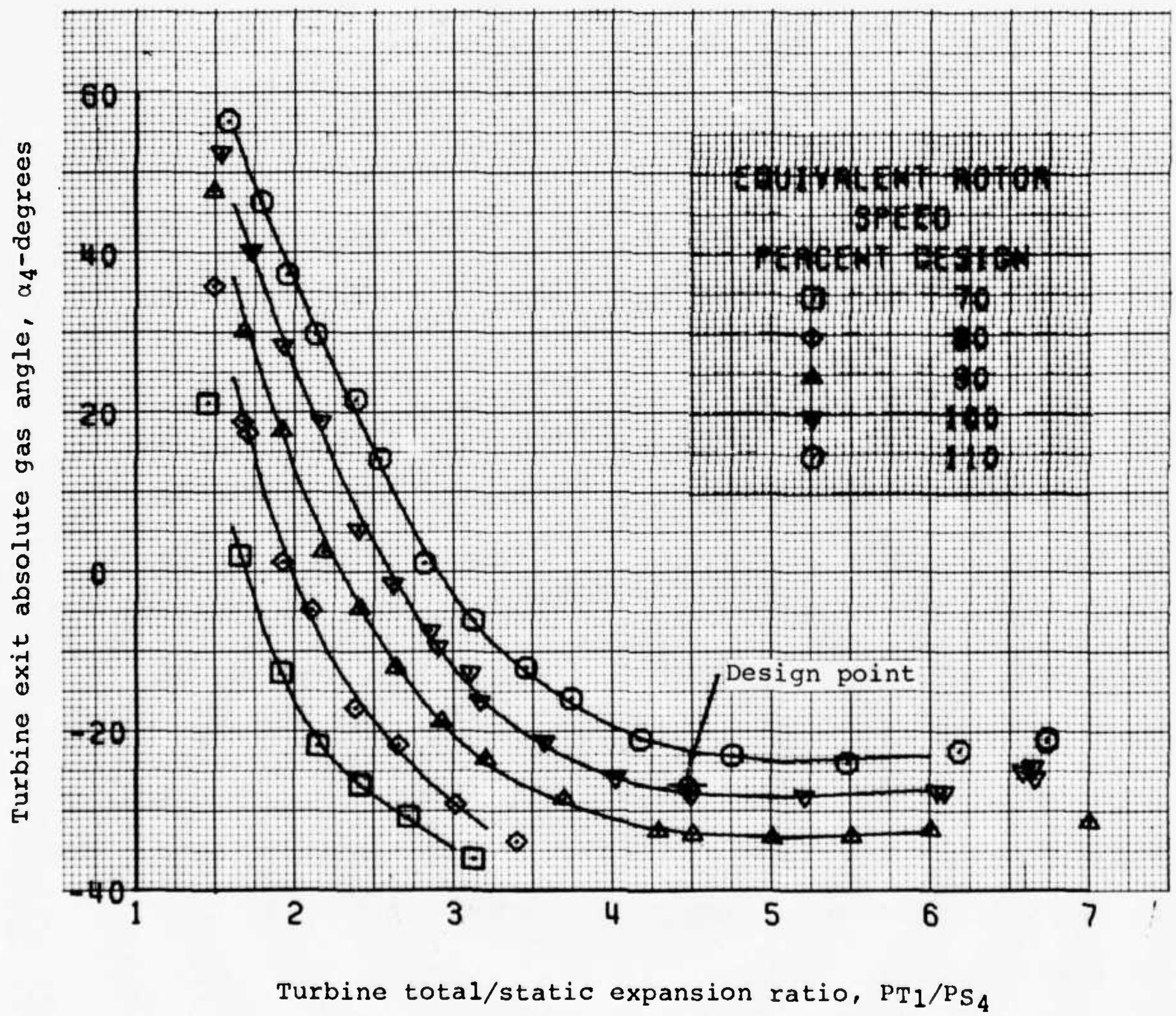


Figure 28 Subscale HTF turbine measured exit swirl angle characteristics

The "smoothed" values of torque, inlet flow rate and calculated turbine total pressure were used to define the HTF subscale turbine rig total/total efficiency (η_{TT}) as a function of total/total expansion ratio ($R_{e_{TT}}$), for lines of percent design equivalent speed. The resulting turbine rig performance characteristics are shown by Figure 29. The definition of η_{TT} used in this calculation was:

$$\eta_{TT} = \frac{\dfrac{2\pi\tau N}{60J}}{\dot{m}_1 \left(\dfrac{\gamma}{\gamma - 1}\right) \dfrac{R}{J} \left[1 - \left(\dfrac{P_{T_4}}{P_{T_1}}\right)^{\frac{\gamma - 1}{\gamma}}\right] T_{T_1}}$$

The aerodynamic design value of total/total expansion ratio is 3.36. The goal efficiency for the HTF subscale turbine rig was 87 percent.

The turbine inlet equivalent flow and total/total efficiency plots were combined to form the rig performance map as shown by Figure 30. The ordinate of this map is turbine equivalent work ($\Delta h/\theta_{cr}$) and the abscissa is the product of equivalent flow rate and speed ($\dot{m}_1 N \varepsilon_1 / 60\delta$). The value of equivalent work is based on design point total temperature and the experimentally determined relationship between $R_{e_{TT}}$ and η_{TT}. The HTF subscale turbine rig design point is noted. As can be seen, the turbine design point equivalent work is about 34.1 Btu/lbm.

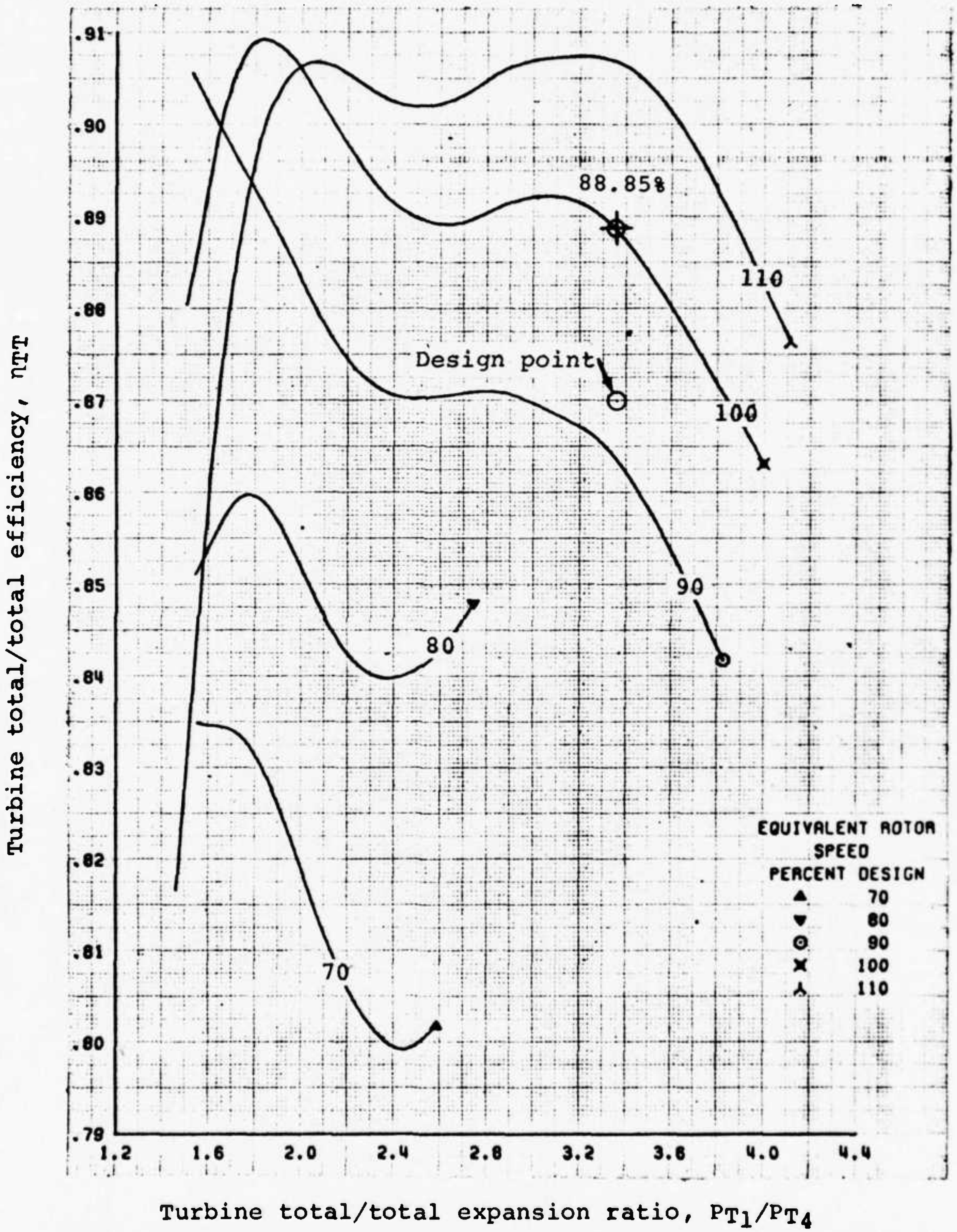


Figure 29 Subscale HTF turbine measured total/total efficiency characteristics

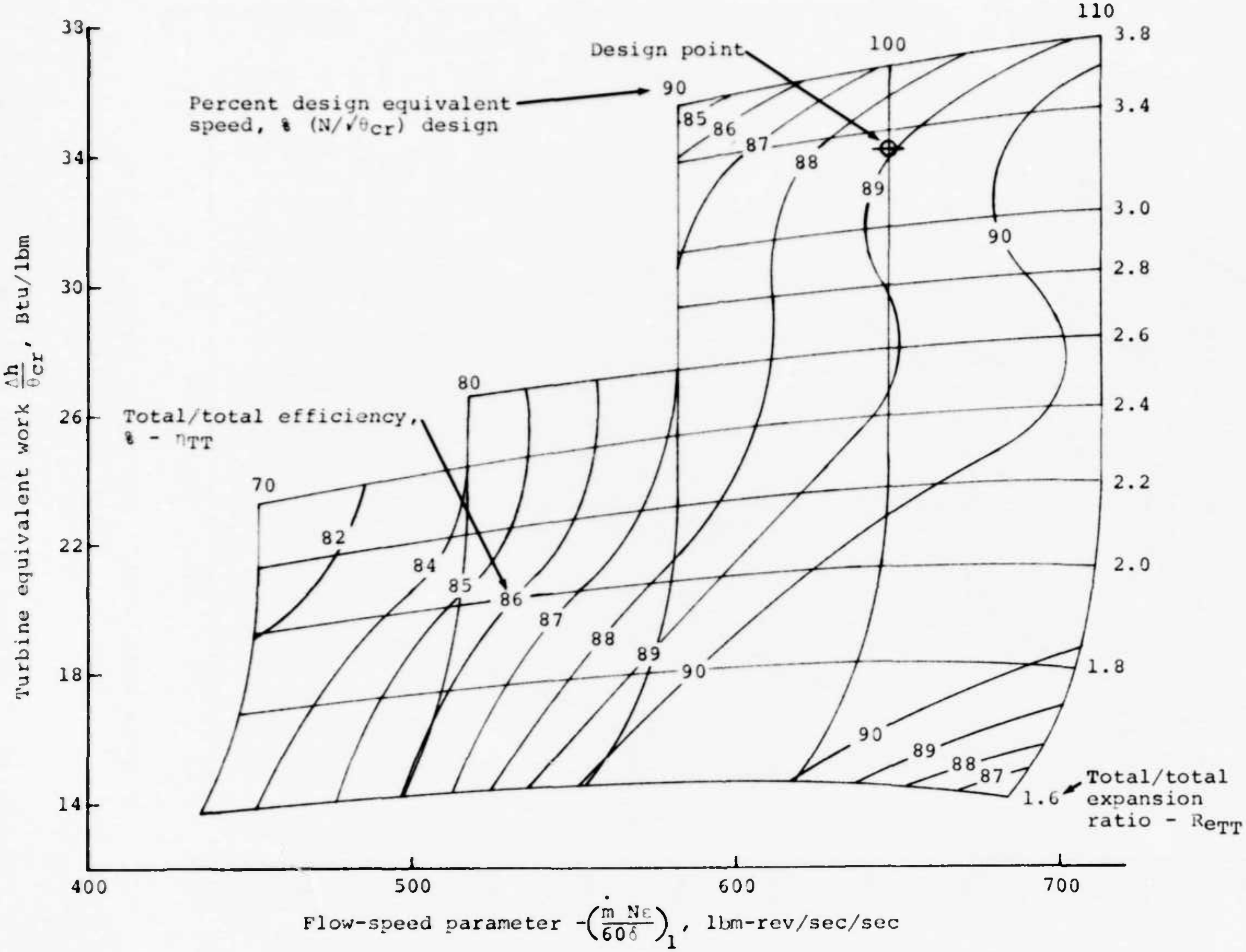


Figure 30 Subscale HTF turbine performance map

The measured relationship between the subscale HTF turbine exit Mach number (MV) and $R_{e_{TT}}$ is presented in Figure 31. The magnitude of exit Mach number at design point total/total expansion ratio was found to be 0.58.

Turbine exit radial surveys of P_{T_4}, T_{T_4} and α_4 were conducted for four selected operating conditions which covered a broad range of exit Mach numbers and swirl angles. Figures 32 through 35 present the radial distribution of total/total efficiency (η_{TT}) and exit swirl angle (α_4) as defined from parameters.

Data Analysis

The measured turbine inlet equivalent flow at design point was 1.511 lbm/sec (Figure 26). This compares to the design value of 1.525 lbm/sec. Thus, the measured flow capacity of the HTF subscale rig was approximately 1.0 percent below design. The vane inlet flow characteristics measured during the stator annular cascade test and the turbine flow characteristics are shown by Figure 36. Excellent agreement exists between these data. This comparison implies that the stator is controlling the flow since the vane and turbine choked flow rates are identical.

The measured equivalent torque at aero-design point total/total expansion ratio was approximately 14.2 ft-lb (Figure 27). This compares to the predicted value of design point torque of

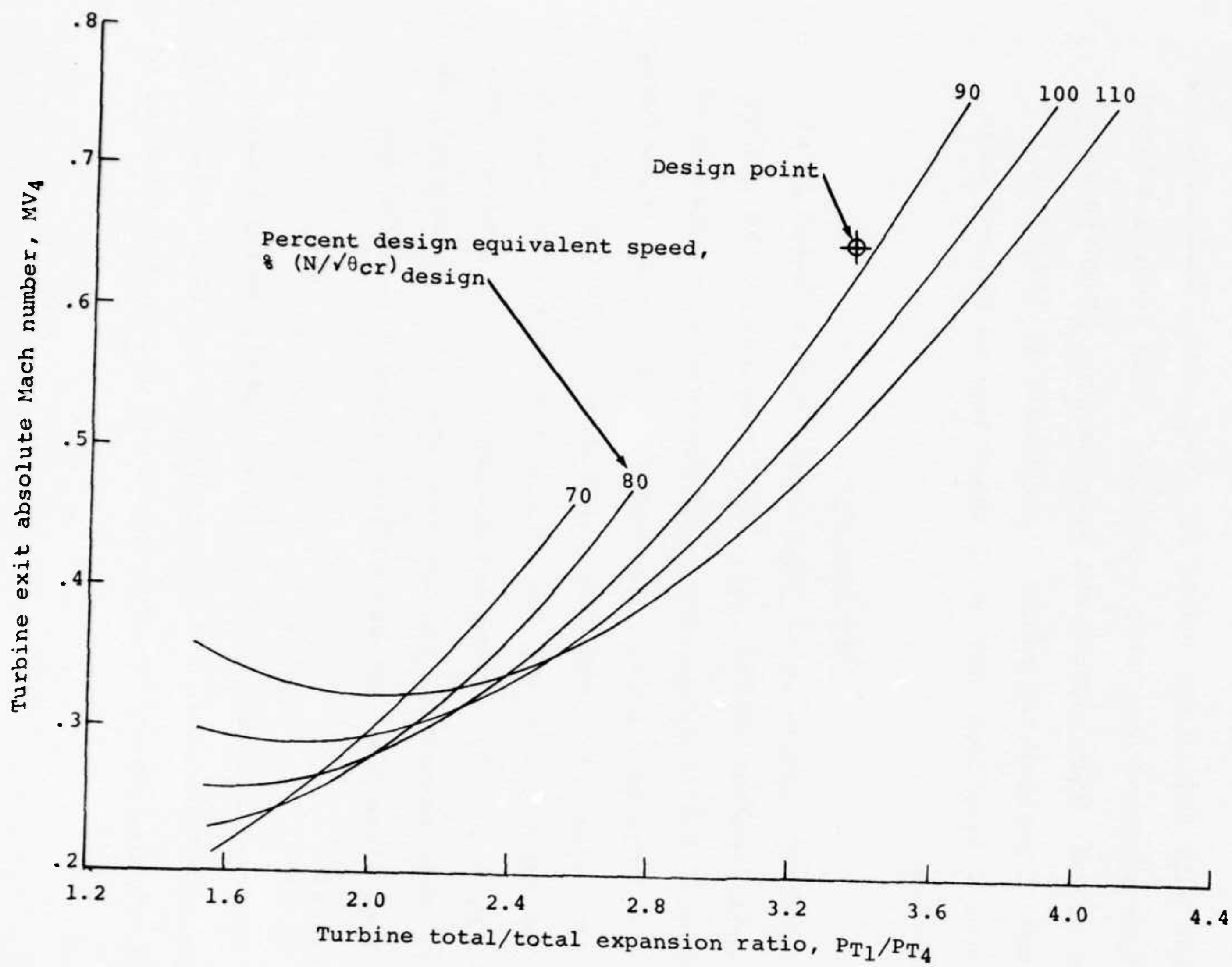


Figure 31 Subscale HTF turbine exit absolute Mach number characteristics

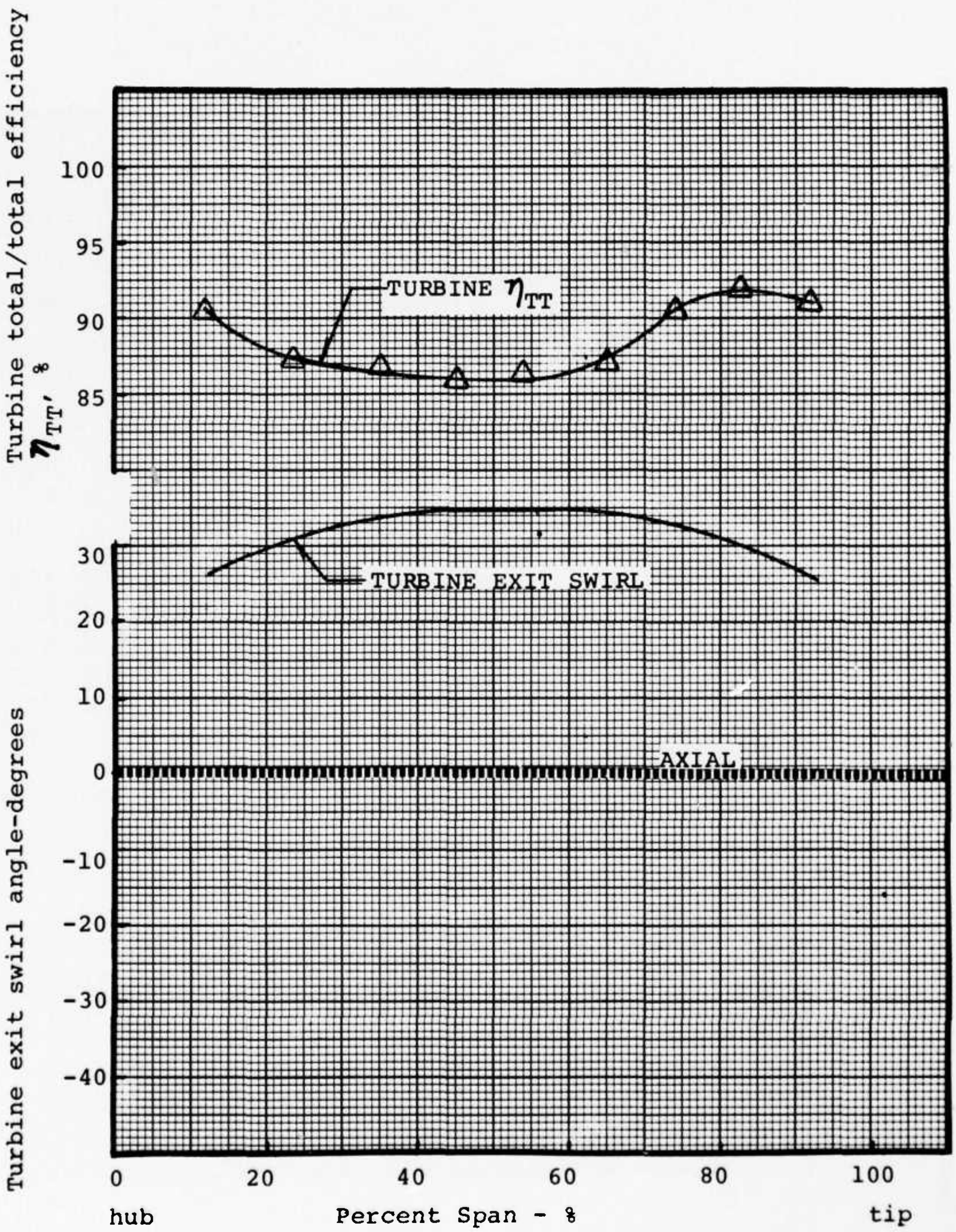


Figure 32 Subscale HTF turbine radial distribution of η_{TT} and exit swirl angle - $N/\sqrt{\theta}_{cr}$ = 100%, $R_{e_{TT}}$ = 1.80

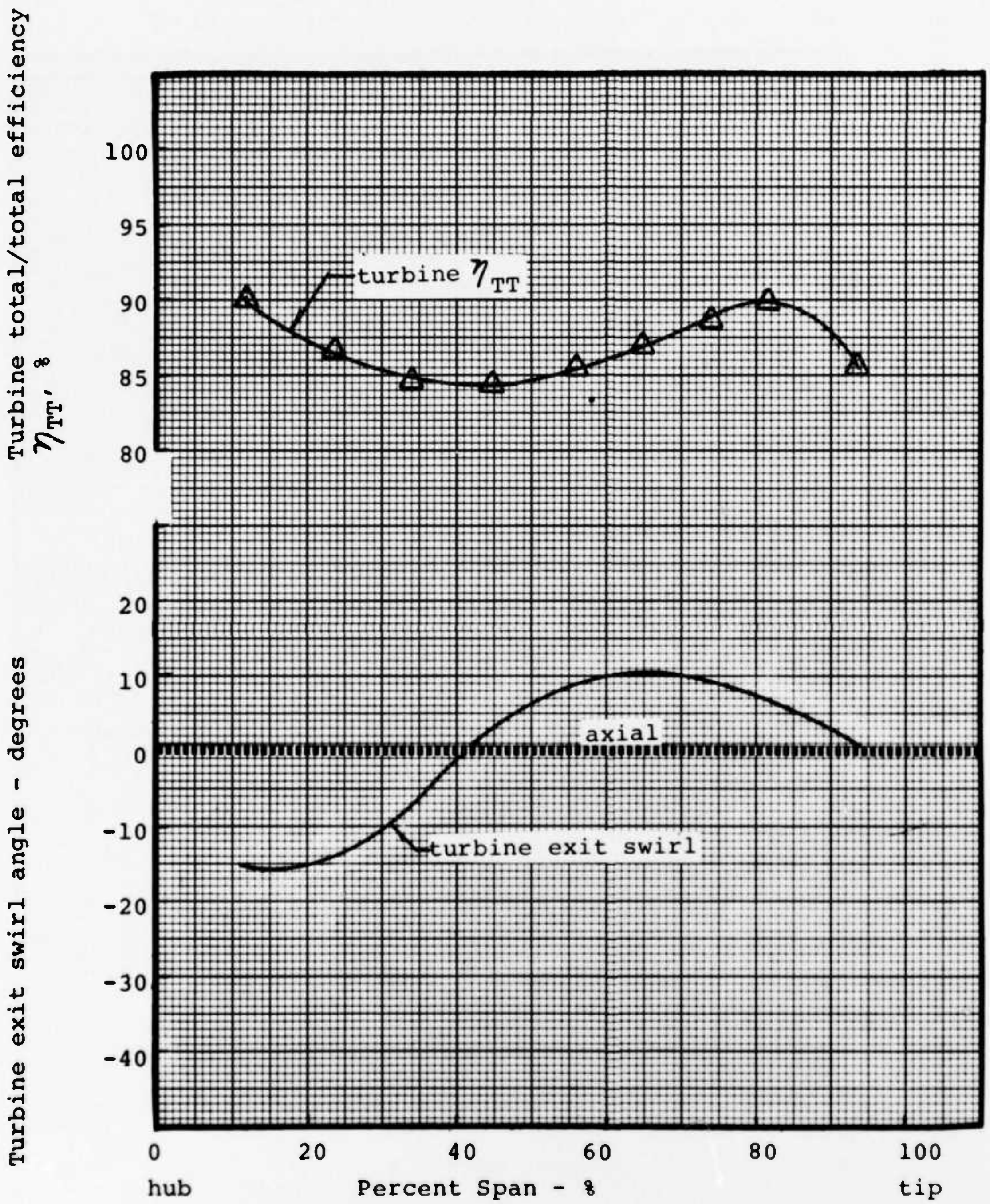


Figure 33 Subscale HTF turbine radial distribution of η_{TT} and exit angle $- \frac{N}{\sqrt{\theta}_{cr}} = 100\%$, $R_{e_{TT}} = 2.44$

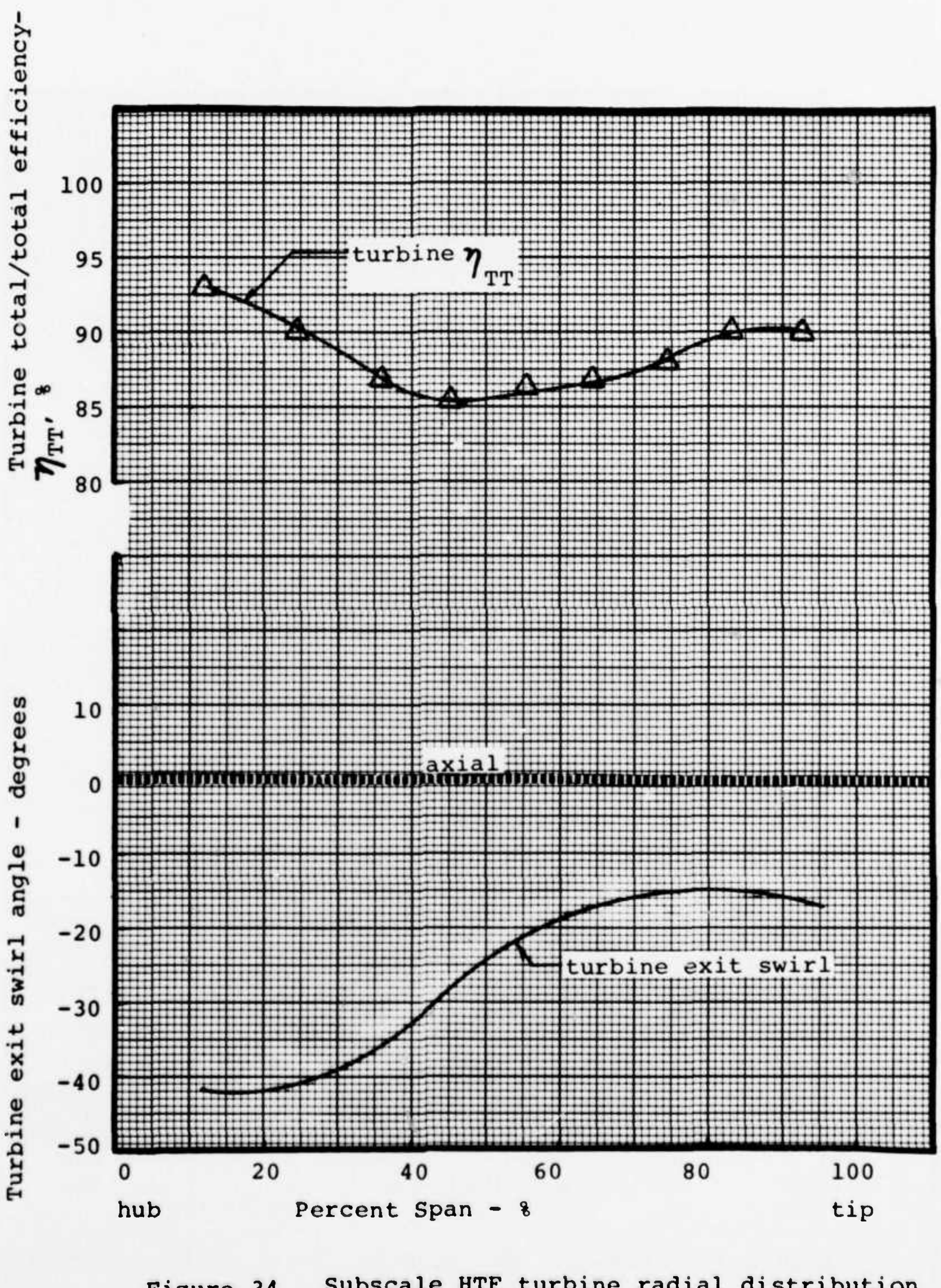


Figure 34 Subscale HTF turbine radial distribution of η_{TT} and exit swirl angle - design point

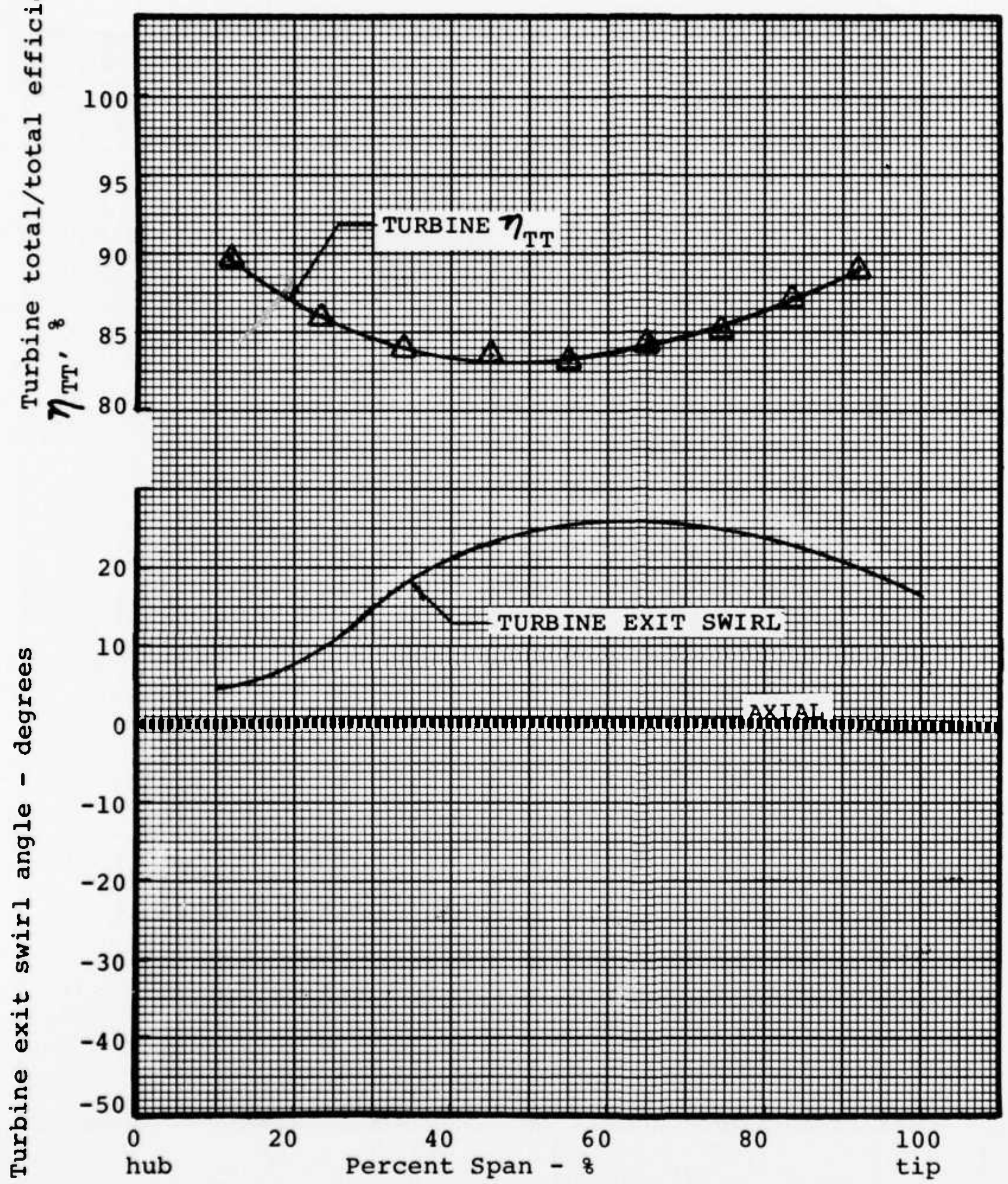


Figure 35 Subscale HTF turbine radial distribution of η_{TT} and exit swirl angle - $\frac{N}{\sqrt{\theta_{cr}}}$ = 80%, $R_{e_{TT}}$ = 1.60

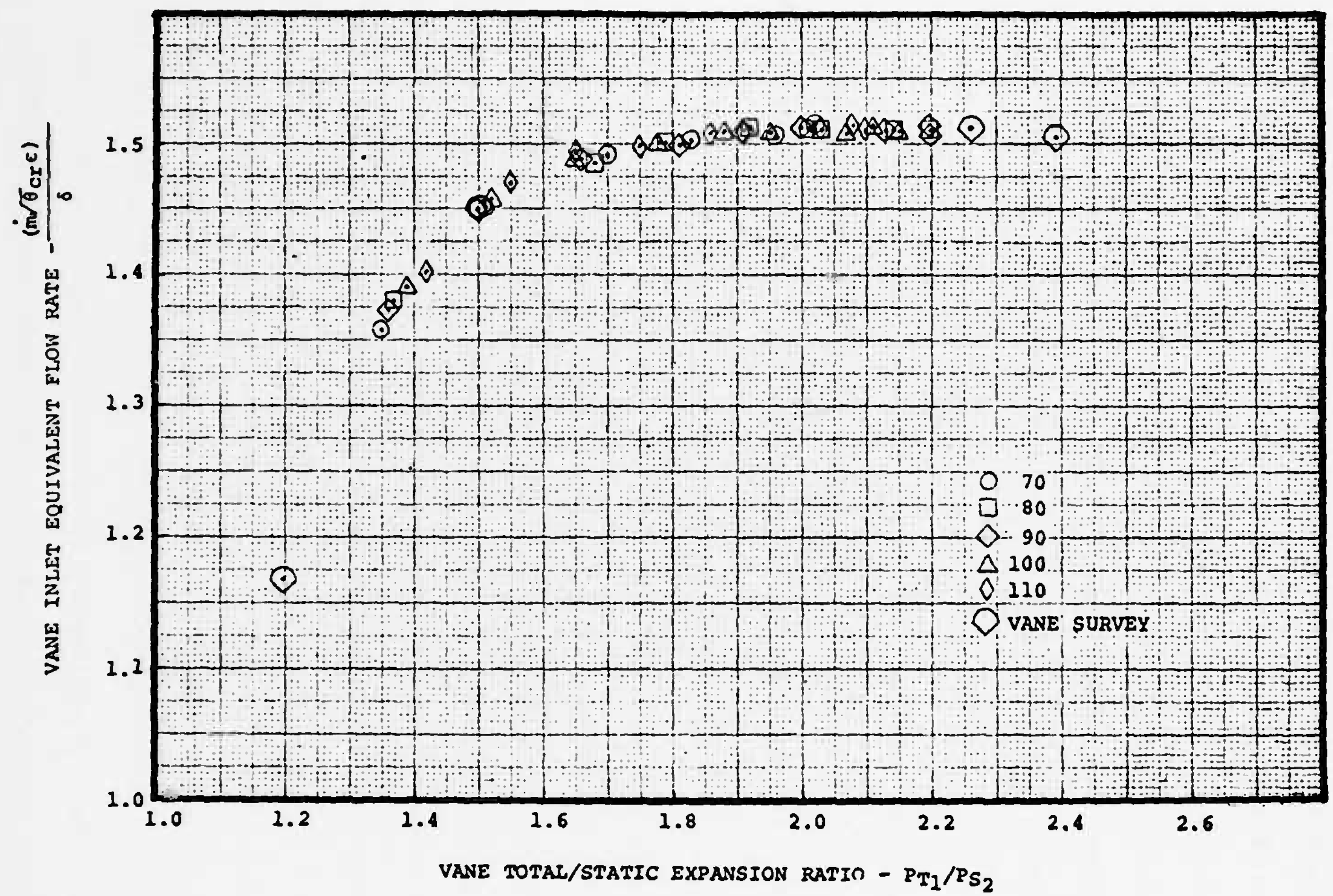


Figure 36 Comparison of stator annular cascade and turbine flow rates

14.1 ft-lb. The combination of increased η_{TT} and decreased flow capacity of the subscale rig accounts for this small difference in shaft torque. It should be noted from examination of this plot that limiting loading torque was essentially demonstrated for both the 100 thd 110 percent equivalent speed. The measured limiting loading torque for 100 percent speed was about 15.5 ft-lb. Thus, the design point has a limiting loading work margin of less than 8 percent.

The measured turbine exit swirl angle at design point conditions (Figure 28) of 27.8 degrees (swirl opposite the direction of rotation) is close to the predicted design value of 26.7 degrees.

The experimentally determined aero-design point total/total efficiency for the HTF turbine rig was 88.8 percent (Figure 29). This compares to a contract goal efficiency of 87 percent. An understanding of the performance characteristics of the subscale turbine can be gained by examining the distribution of hub and tip static pressures through the turbine. Figures 37 through 41 present the vane and blade exit static pressures for each speed line over the range of $R_{e_{TT}}$ investigated. The data shows that 70 percent speed line has low rotor reaction at all values of $R_{e_{TT}}$. At a given value of $R_{e_{TT}}$, increasing speed provides greater rotor hub reaction. The 100 and 110 percent speed lines have positive reaction throughout the operating range. The measured rotor hub static pressure

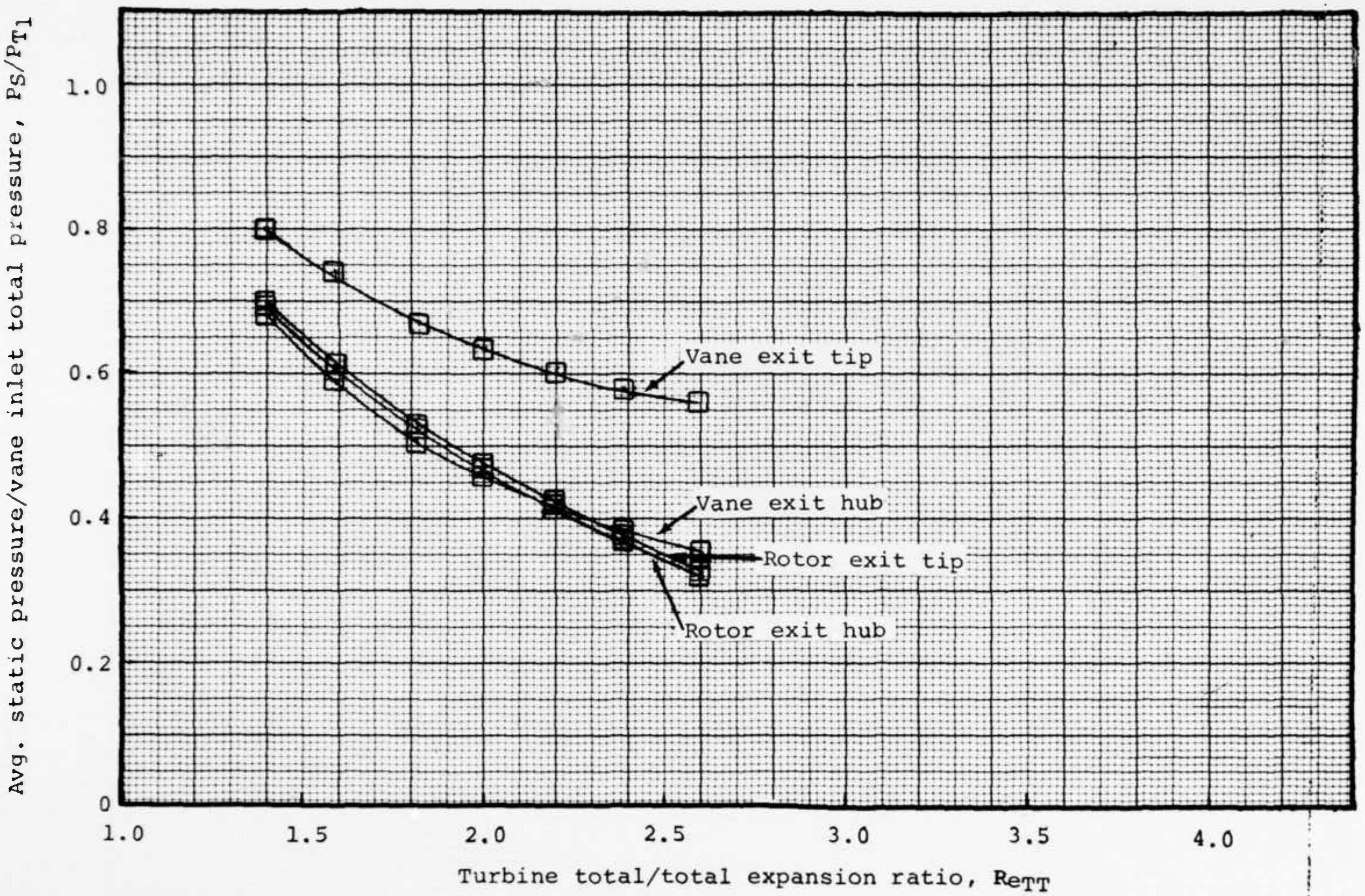


Figure 37 Subscale HTF turbine measured hub and tip static pressures - 70% equivalent design speed

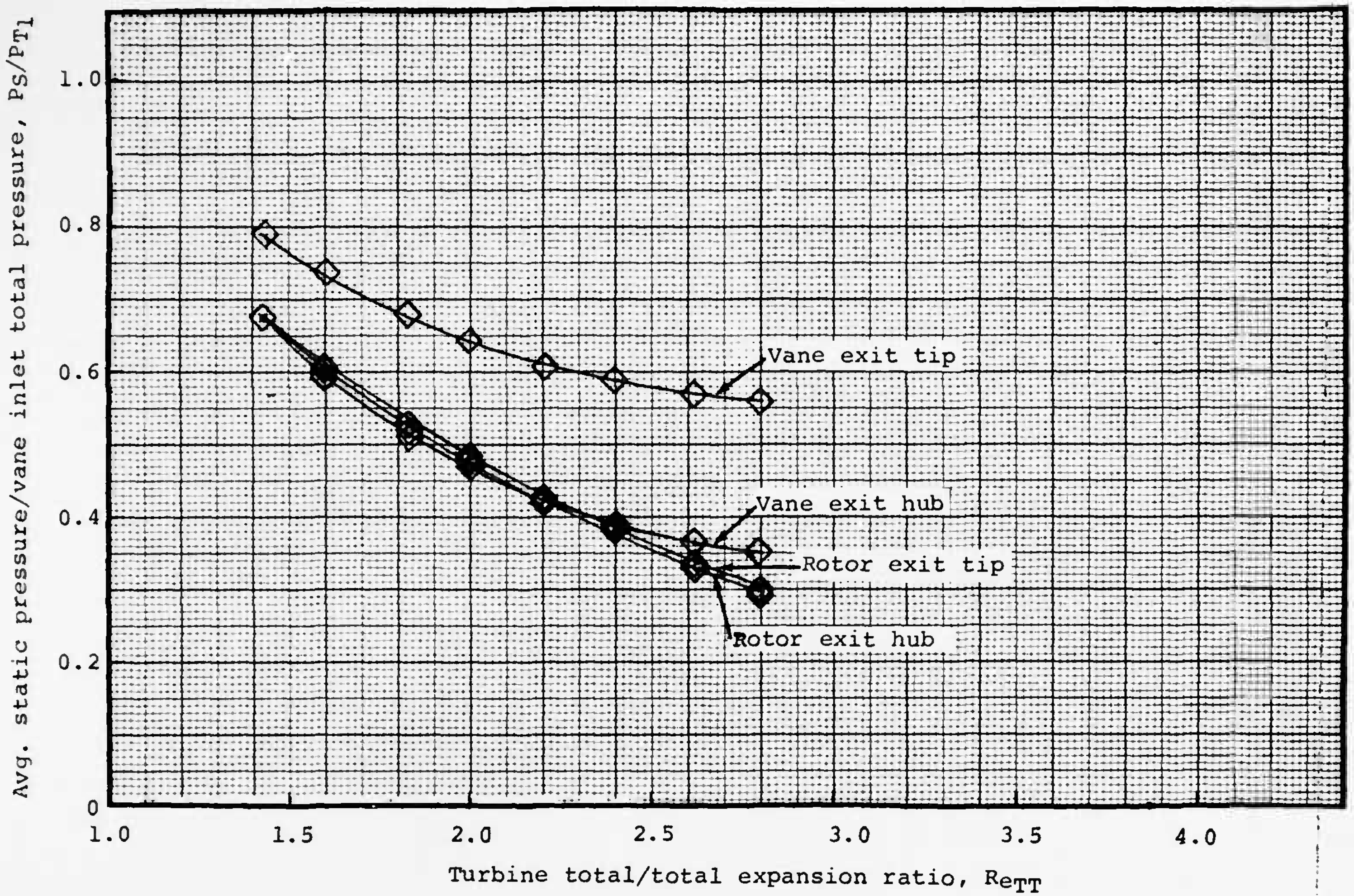


Figure 38 Subscale HTF turbine measured hub and tip endwall static pressures - 80% equivalent design speed

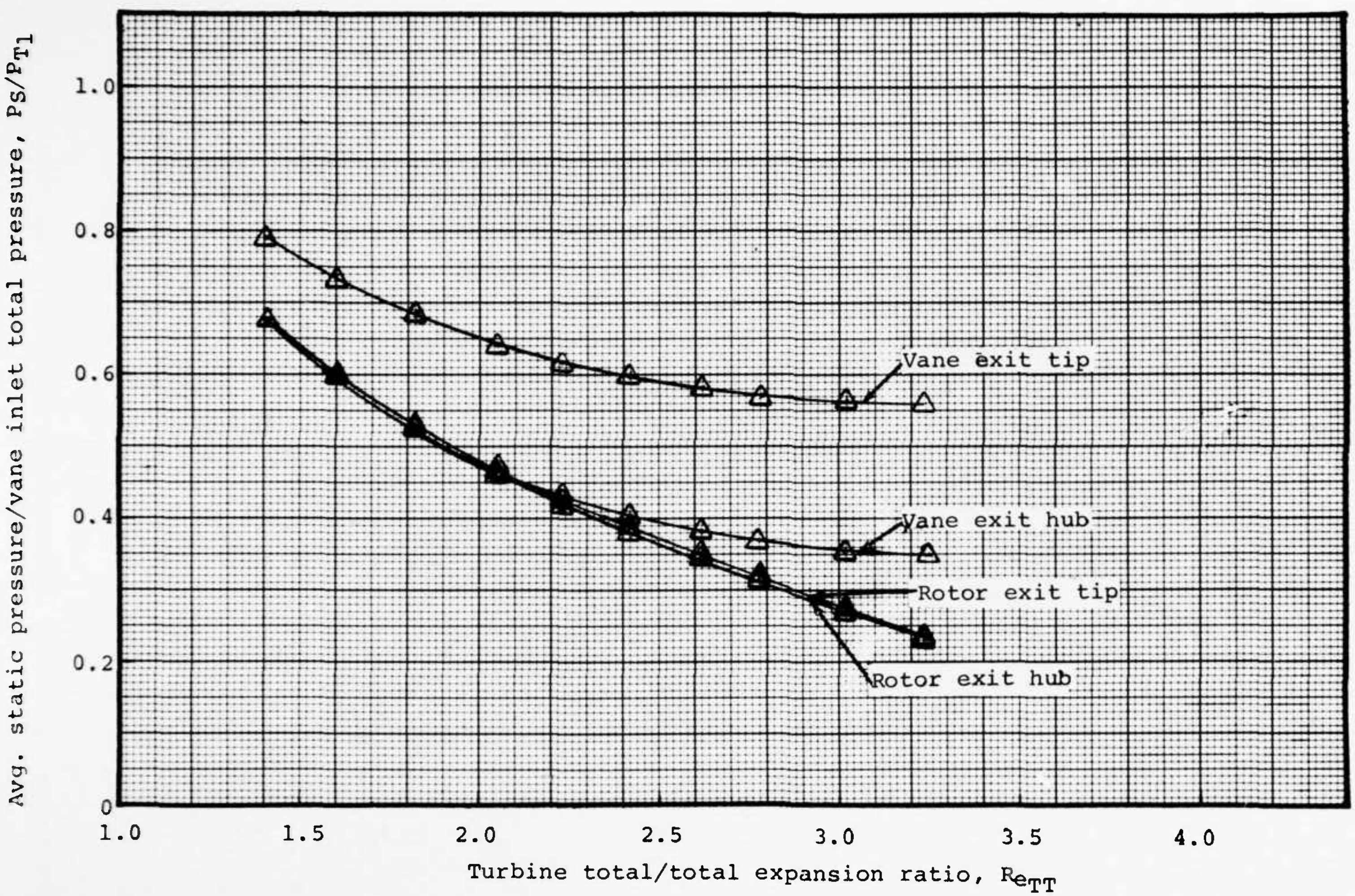


Figure 39 Subscale HTF turbine measured hub and tip endwall static pressures - 90% equivalent design speed

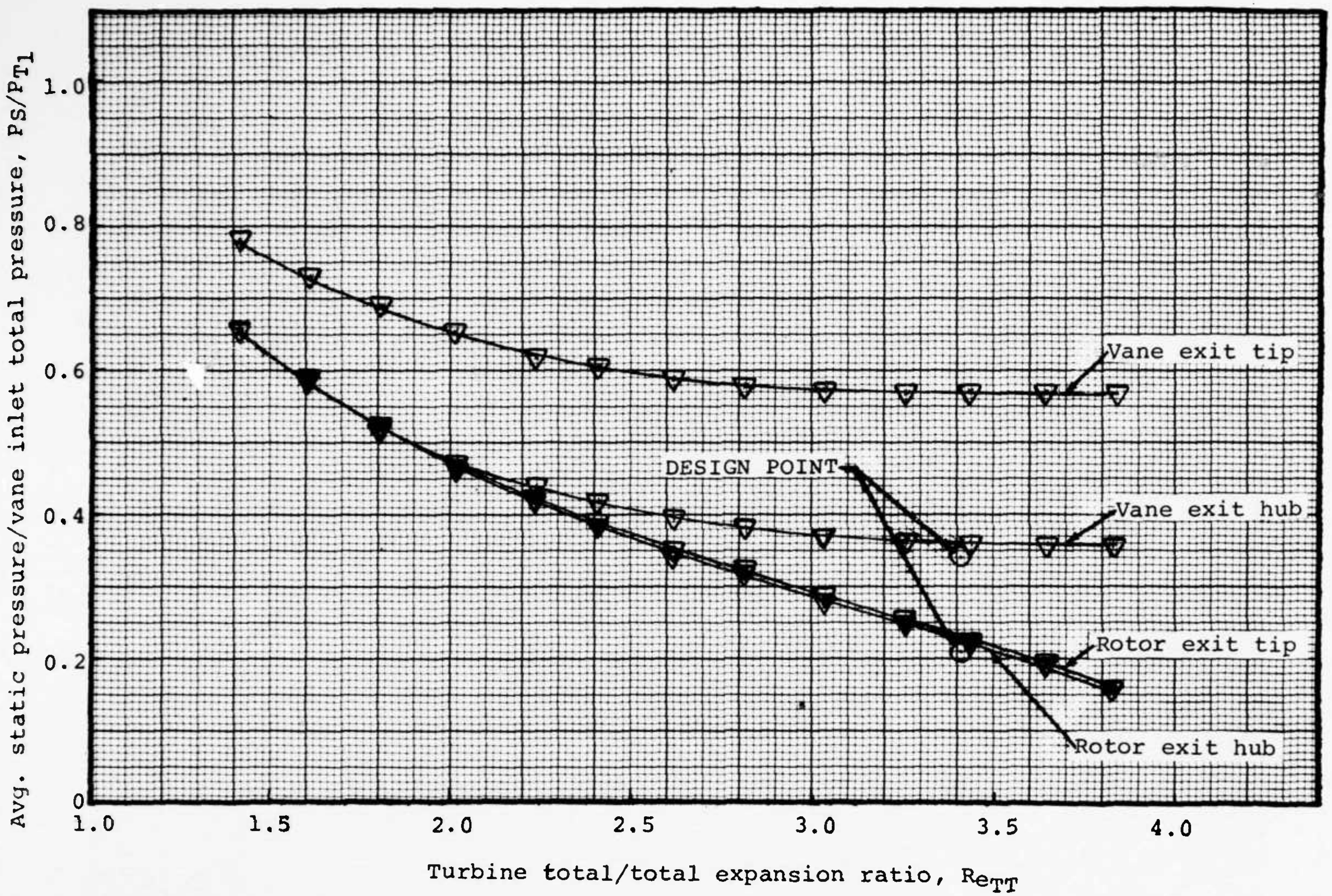


Figure 40 Subscale HTF turbine measured hub and tip endwall static pressures - 100% equivalent design speed

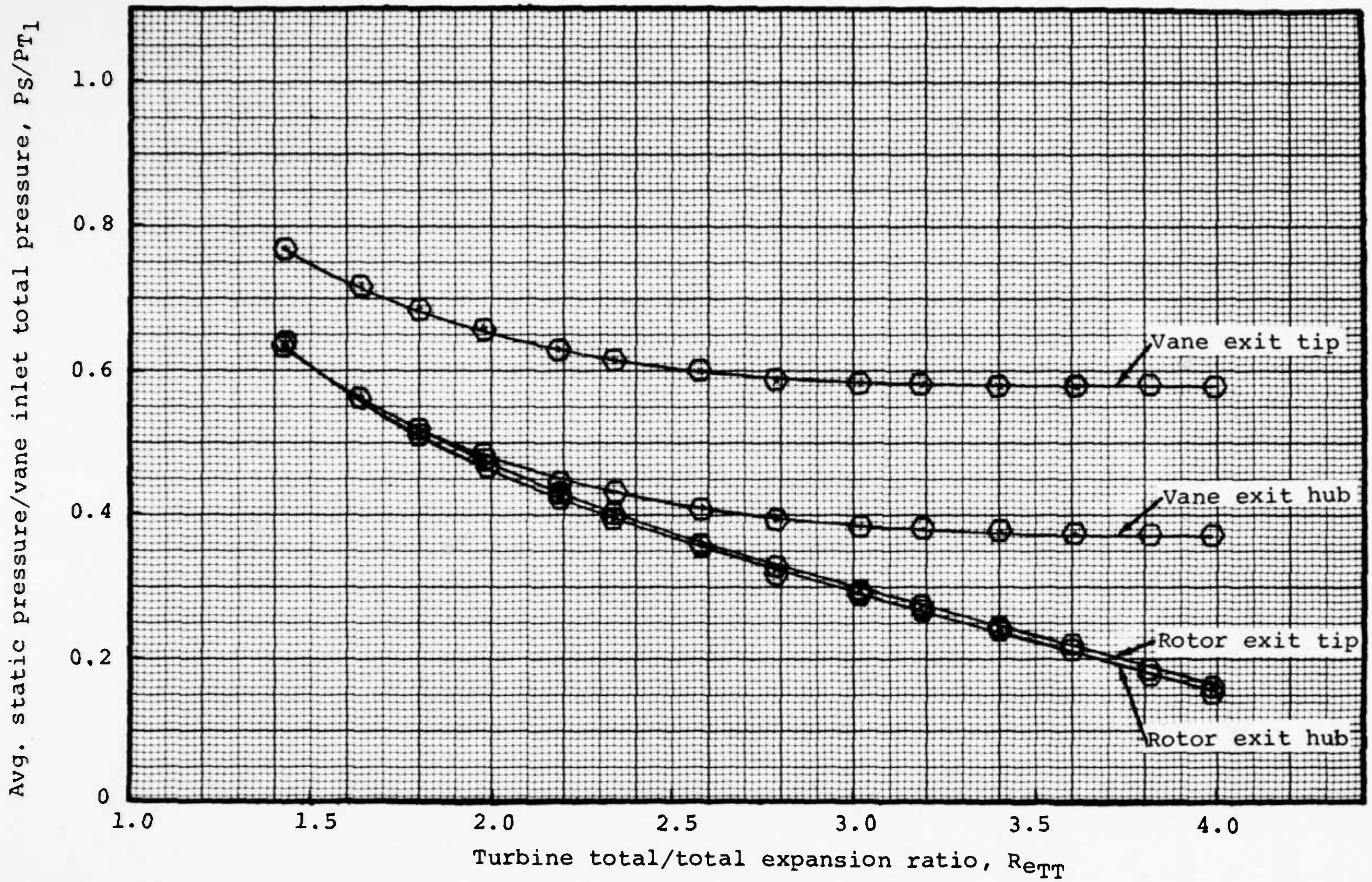


Figure 41 Subscale HTF turbine measured hub and tip endwall static pressures - 110% equivalent design speed

reaction (static pressure change across the rotor/static pressure change across the stage) at design point conditions was 0.162. This matches the predicted design point value of reaction. However, as indicated by the slightly lower static predicted Mach number levels at both locations are slightly higher than measured.

The subscale HTF turbine performance map (Figure 30) was limited at the lower speed lines by torque constraints on the DDA Small Turbine Research Facility. At the higher speeds, the turbine operation was limited by inlet total pressure constraints. However, the turbine map limiting loading line was experimentally defined for both the 100 and 110 percent speed lines. This map indicates the subscale HTF turbine rig demonstrated an equivalent work $\frac{\Delta h}{\theta_{cr}}$ of 34.1 Btu/lbm at a total/total efficiency (η_{TT}) of 88.8 percent.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The design, fabrication and cold air testing of a subscale HTF turbine has been completed. All the program goals as set forth in the contract were satisfied. Table 15 is a tabulation of a comparison between measured and predicted design point performance parameters.

TABLE 15

Comparison of Measured and Predicted Design Point Aerodynamic Parameters

	Design	Measured
Inlet equivalent flow rate, $\frac{m\sqrt{\theta_{cr}}\,\varepsilon}{\delta}$	1.525	1.511 lbm/sec
Equivalent work, $\Delta h/\theta_{cr}$	33.4	34.1 B/lbm
Total/total efficiency, η_{TT}	87%	88.8%
Turbine exit swirl, $\bar{\alpha}_4$	26.7°	27.8
Turbine exit Mach number, MW_4	.65	.58
Rotor hub reaction, $\frac{\Delta P_S \text{ rotor}}{\Delta P_S \text{ stage}}$	.162	.161
Limiting load work, $\Delta h/\theta_{cr})_{LL}$	36.5	37.2 B/lbm

These data illustrate the extent of the success of the subscale HTF turbine program.

Additional work is recommended to enlarge the technology base being developed. The following areas of work are desired:

- Evaluation of the subscale HTF turbine performance employing a vane reset. The vane would be reset in an "open" position characteristic of maximum turbine inlet total temperature.
- Design, fabricate and test of an EGV compatible with the range of exit Mach numbers and swirl angles of the HTF turbine.
- Experimentally investigate methods of improving the HTF vane performance in the near hub region.
- Evaluation of the performance characteristics of a subscale HTF turbine configuration designed for a higher rotor reaction. This would require resetting the rotor "closed" in the current rig. The amount of reset would be defined from exit swirl and/or exit Mach number constraints.

The subscale HTF turbine as tested is consistent with the variable pressure ratio full size turbine vane in a "closed" position (characteristic of minimum RIT cruise condition). A second performance mapping is suggested using a vane reset in the "open" position as a method of simulating the variable pressure ratio requirements of the full size HTF turbine. The rotor assembly for this test program would be unaltered.

The application of the HTF turbine in a turbojet engine configuration will require an EGV due to the exit swirl. The design of an EGV compatible with the single stage HTF turbine is an integral part of the HTF aerodynamic technology base.

The subscale turbine vane exhibited an area of high loss in the near hub endwall region. It is thought that a major portion of this loss came from an excessive boundary layer build-up upstream of the vane inlet. The current vane assembly would be retested employing a rig modification to form a baseline for evaluating alternate vane designs.

Test data indicates the subscale HTF turbine has more limiting loading work margin than predicted. Since a limiting loading work margin fixes the turbine minimum cruise RIT, it is of interest to increase design point equivalent work. It is suggested that the vane remain unaltered and the rotor "closed". This will have the effect of increasing the rotor hub reaction.

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